Geologic Development of Jordan

-Evolution of its Rocks and Life-

Klaus Bandel and Elias Salameh

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يتحمل المؤلف كامل المسؤلية القانونية عن محتوى مصنفه ولا يعبر هذا المصنف

عن رأي دا ئرة المكتبة الوطنية او اي جهة حكومية اخرى

Cover Page: Slates of Abu Barqa Formation, East of Wadi Araba

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Content.

Geologic Development of Jordan

-Evolution of its Rocks and Life-

Preface

In this book the historical geologic development of Jordan since Precambrian times is worked out and documented. It is based on up-to-date knowledge and field and laboratory work both in Jordan and Germany. The book integrates available publications, reports and master and doctoral theses carried out on Jordan and beyond when that information appeared necessary for the understanding of the geology of Jordan and its evolution.
The idea of the book arose during a field trip to Waqf as Suwwan impact crater when the first author, Klaus Bandel was explaining to two accompanying German students the palegeographic evolution of some Upper Cretaceous formations in Jordan, and was asked by the second author, Elias Salameh to document his knowledge about the paleogeographic development in a publication, because that knowledge is not found in details in any available document.
The book contains details on paleogeography, paleontology, rock units and their formation, environments and living spaces and conditions of organisms based on scientific documentations, and on own studies and experience.
The last chapter of the book deals with the recent human history of Jordan as conditioned by its climate, geographic and geologic set-up where water availability has been the sole limiting factor for human development.
It is hoped that this book will fill a gap in the libraries and will be of help to students and geology scholars to increase their understanding on the evolution of Jordan's geology. It is thought of to serve students with adequate familiarity with geology and its terminology, with physical geography and particularly the geology of Jordan.
Sincere thanks are extended to Prof. Dr. Heinz Hötzl, University of Karlsruhe and to Prof. Dr. Hani Khoury, University of Jordan for their critical review of the book contents, their suggestions and their advice. Thanks are also extended to Dr. Marwan Alraggad for making available some photographs and for his kind help in formatting the book content.
Thanks are also extended to the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung)/ SMART Project (Sustainable Management of Available Water Resources with Innovative Technology), from which budget that was allocated to the University of Jordan, this book has been printed.
For us, the authors this book has a personal context, because it arose from our field work, detailed direct knowledge and observation of the geology of Jordan in addition to our teaching experience both in lecturing and field work with students.

The authors

For locations please see Appendices.

1. Precambrian of Jordan:

Basement:

The old land surface formed before the deposition of sediments and the conspicuous Cambrian sandstones in Jordan consists of a plain of a crystalline base (Fig.1). Here rocks formed while they were at least 10-15 km below surface. They represent the metamorphic roots of formerly existing mountains. It was part of a supercontinent called Rodina that has been suggested to have existed about 1200 Million years ago and around 900 Million years ago to have become split into several continents by the formation of new oceans. Rodina is interpreted to have included the old continental crusts which were subsequently split by oceans forming between them and are now present in parts of South America, Africa, Antarctica, Australia, Madagascar and India. The oceans formed when the old continent Rodina was split up and they were interpreted to have been subducted again during the Pan African orogeny about latest 550 Million years ago. The reconstruction of the ancient geography is very difficult and insecure since many of the involved rocks have disappeared and/or changed much due to metamorphism. Termo-tectonic events, during which molten rocks from the deep of the crust moved toward the surface, can be dated by analyzing the composition of stable and unstable isotopes within crystals. These crystals grew anew when molten rock became solid rock.

Fig. 1: Precambrian crystalline base in Wadi Yutum with the phosphate railway and the many dykes transecting the metamorphic granite and gneiss.

The deep reaching truncation of the former mountain ranges is exposed in the southern area of Jordan. Its surface is the result of weathering that may have lasted for hundreds of Millions of years. Mountains were eroded that were at times several kilometers high. The crystalline base of SE Jordan represents part of the northern portion of the basement exposure that surrounds the Red Sea. It belongs to the Arabo-Nubian shield that consists mainly of metamorphic gneisses and granitic plutons and belongs to a continent called "Greater Gondwana". The metamorphosed gneisses in part originated from sediments and in part from magmatic rocks before becoming transferred due to heat and high pressure. They have subsequently been transected by numerous dykes of light and dark colors creating a zebra pattern as can be noted in the mountain outcrops on both sides of the highway descending in Wadi Yutum from the former Precambrian peneplain near Wadi Ram and near Quweira to the coast of the Gulf of Aqaba. Here the crystalline basement rocks composed of granitic material with a composition predominantly of feldspar, quartz and mica is riddled by many dikes of differing dark or light coloration depending on its predominantly acidic to basic mineral composition (Fig. 2). Acidic is with much quartz, and basic has no quartz and much feldspar.

Fig. 2: The crystalline basement is transected by many dykes composed of dark and light minerals, view near Quweira.

Fig. 3: Cambrian and basement drowned in the alluvial plane at the road to Wadi Rum

Recent exposure of the crystalline base of south Jordan is connected to the formation of the Red Sea. Before rifting this whole area was uplifted and the Red Sea rift broke into the central part of this high. This area encompasses SE Jordan together with western Saudi Arabia and the Red Sea Hills in SE Egypt and the Sudan. Here most of the sediment cover had been eroded exposing the old continental surface, near Wadi Rum with the old Precambrian surface partly exposed, and in Wadi Yutum towards Aqaba the crust below is eroded and exposed on the valley sides (Fig. 3).

The ancient surface of the continent is exposed at the base of the Cambrian sandstones (Fig. 4).
. It documents weathering due to which the crystals of the rocks detached from each other forming sand with angular grains and with the feldspar. This material has been partly reworked when the Cambrian deposits formed, and it also included quartz pebbles that have been shaped by rivers running here and the wind blowing over the plains, polishing their surfaces. By this way some of the pebbles were facetted. This final period of predominantly physical erosion was followed by a global warming during the Cambrian. The erosive products on the plain may have been shaped under cold climate and above them deposits may have formed under warmer conditions, with physical weathering prevailing over chemical decomposition, so that feldspar was preserved.

Fig. 4: The flat Precambrian erosion surface near Quweira overlain by Cambrian sandstones.

2. Late Precambrian of Jordan with Saramuj Conglomerate and Abu Barqa Volcanic series.

Along the western edge of the crystalline base in Jordan after the erosion of the Precambrian mountains to their crystalline base and before begin of the deposition of the Cambrian sandstones two quite different deposits formed. The more northerly of these consists of coarse to very coarse fluviatile sediments with channels oriented in about N-S direction. This fluviatile deposit called Saramuj Conglomerate is exposed along the foothills to the east of the southern end of the Dead Sea near Ghor Safi. Exposures end just north of the lower Wadi Hasa. Regarding the Saramuj deposits it remains a riddle, where the often very large rounded boulders present in the stream canals have come from and which mountain was their source. The more southerly Precambrian outcrop is a complex of volcanic rocks and sediments deposited on a base of conglomerates which cover granitic basement, the Abu Barqa (it has also transferred from the Arabic as Abu Barka, Wadi Abu Burqa) to the North of Gharandal and to the southwest of Petra. It lies in the eastern mountains bordering Wadi Araba. Here within a caldera lake the earliest signs of life preserved in Jordan have been produced by cyanobacterial mats.

Within the Late Precambrian an extended ice-age came to its end, which was reconstructed to have ended as Gondwana became fully assembled. Within the Late Proterozoic and perhaps its subunit the Vendian period (about 600-550 million years ago) the Arabian platform had been reconstructed to become situated in the area of tropical to subtropical climate on the southern hemisphere, situated approximately at latitude 30° S. The global glaciations may have even taken hold of former tropical latitudes and the scenario of a “snowball earth” has been suggested, when the oceans had also been covered by ice. The continent “Greater Gondwana” may have had a role in creating the ice-age conditions during the Late Precambrian by having the South Pole on it. The extremely long periods of time involved here result in some uncertainty regarding the geographic position of the area, as well as climatic conditions that may have persisted. Information has to be collected from the type and composition of the sediment encountered and conditions of its formation were quite different from those present now.

The margin of the plate of crystalline metamorphic rocks as found in the area between Wadi Rum and the Gulf of Aqaba was fractured by a fault system that is thought to have had a quite similar orientation as that of the modern Gulf of Aqaba, Wadi Araba, Dead Sea and Jordan Valley Rift zone. In that rift zone on the edge of Gondwana that may be almost parallel to the modern Jordan Rift, volcano-conglomeratic series formed. They rest on the pene-plained former central mountain range that had been eroded down to its metamorphic roots and faulted downwards compared to the area in the SE of it. Similar Late Proterozoic rocks are also known from SE Israel (Elat Conglomerate) and in the subsurface of eastern Jordan with immature clastic rocks associated with various igneous rocks.

Next to the southern end of the Dead Sea the Saramuj Conglomerate had its depositional setting perhaps similar to that of a fault controlled intermontane basin that may have been similar to the recent Wadi Araba Rift valley. It has also been interpreted as Pan-African molasse sequence and in that case would have formed in a depression next to the mountain chain. If that were the case, the Pan- African orogeny should have occurred at about the same time or a little earlier than of the deposition of the Saramuj Formation.

While the Saramuj Formation is exposed to the East of the southern end of the Dead Sea near the town Ghor Safi, the series of slates and tuffaceous beds of the Wadi Abu Barqa Formation is exposed about 80 km to the south of the Dead Sea in the central Wadi Araba. The relation of Wadi Abu Barqa Formation to the Saramuj Formation is not resolved but regarding the type of deformation of these rocks Abu Barqa Formation is older than the Saramuj Formation. Both sequences underlie the Cambrian sandstones with an angular unconformity. They may in part have been shaped under cold climate but the influence of ice during their formation has not been recognized.

The Precambrian basement just east and southeast of Wadi Gharandal and thus only a few kilometers (about 5) to the south of Wadi Abu Barqa consists of metamorphic and plutonic rocks that have been transected by numerous light and dark dikes and were evenly truncated into a pene-plain onto which the Cambrian Sandstones were deposited. About 5.5 km north of Wadi Gharandal at the mouth of the Wadi Abu Barqa, a basal conglomerate overlies rocks of a basement that had been affected by the same diagenesis as the rest of Abu Barqa Formation (Fig. 5). It has, therefore, become more altered than the actual Saramuj Formation as found in its type locality near Ghor Safi, about 80 km further north. Abu Barqa Formation of the late Precambrian formed in the proximity of volcanoes and by their activity. It includes about 120 m of tuffaceous sediments overprinted by cyanaobacterial mats and is covered by volcanic tuffs including ignimbritic tuffs transected by volcanic dikes and sills and several hundred meter thick deposits of volcanic material. The sediments were affected by a weak metamorphosis and clay stones of the Wadi Abu Barqa Formation have been transformed into slates due this diagenetic processes related to the pressure of the overburden. The whole thick series was thus deformed, slightly metamophosed and inclined with a dip to the east. It was afterwards eroded to form a hilly landscape. No indication of shistosity is found in the Cambrian sediments above. The presence of slate indicates that an orogenic cycle distinguishes the Precambrian Abu Barqa series from the overlying Cambrian sandstones.

The Abu Barqa Formation is largely the product of rhyodacitic volcanism with ignimbritic and pumice products. Both of these were blown out of the volcanic vent when it was productive, but while ignimbritic lava is expelled as very hot bombs which fuse with each other when they land on the surface, pumice is foamy lava with many gas bubbles in it and falls to the ground as solid but light bomb, which may float on water. The pumice is a very porous, white rock with sanidine and biotite inclusions and the bombs were usually flattened subsequently when the sediment became compacted. Volcanic material usually fell onto the bottom sediment from above and there are no dikes that cut through the series of slates exposed in the mountainous region just to the south of the deep valley of Wadi Abu Barqa. But the whole series became intruded by at least one thick sill which represents a former layer of magma that squeezed itself between the sediments and parallel to their surface.

An up to 6 m thick arkose or conglomerate composed of angular and little rounded pebbles of up to 30 cm in diameter locally overlies and covers the crystalline base. These pebbles consist predominantly of granite and crystalline rock with porphyritic structure, more rarely of gneisses. The base on which this coarse sediment rests has irregular surface and consisting of pinkish granite that is transected by many dikes. In other localities, nearby the base of the sedimentary rocks of Wadi Abu Barqa Formation consists of granite without any intermediating conglomeratic cover. Near Elat also boulder beds and conglomerates are connected to volcanic flows, dykes, pyroclastica and ignimbrites and may be of the same age as the Abu Barqa Formation, but displaced about 110 km to the south by the Araba fault (Jordan Rift fault).

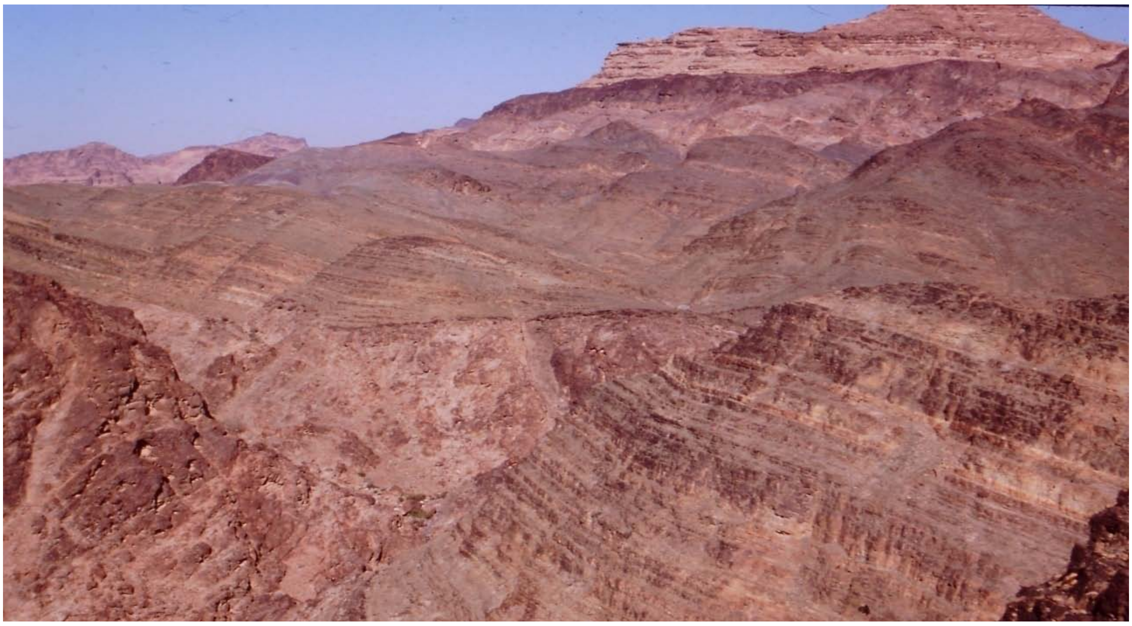

Fig. 5: Basal granite at the left overlain by tuffites with angle from the Abu Barqa mountain with view to the North and Cambrian sandstone on top.

The basal beds of Abu Barqa Formation consist of alternating tuffaceous material and greenish shales and slates. The sediment formed around the volcano consists predominantly of reddish or gray, dense rocks rich with inclusions of quartz and quartz-porphyry fragments. Where fine sediments occur right on the crystalline base, the solid basement may be found covered by a calcareous stromatolite that has the characteristic laminar and nodular structure and is found at its former place of growth. Some of the stromatolites have a digitate structure. They are the oldest known fossils preserved in Jordan and thus the oldest known traces of life in the region (Fig. 6).

Fig. 6 a,b: Stromatolites from the basal part of the series of tuffaceous slate of Abu Barqa Formation.

The organisms responsible for stromatolite formation are photosynthesizing cyanobacteria (blue green algae) which grow in thin layers. The single cells without nucleus are arranged to form elongate rows surrounded by glutinous sheets. Thus the individual filaments can trap fine grains and around them lime can be deposited. Afterwards a fresh layer is formed on top of it producing the layered appearance. Cyanobacteria lived predominantly in the shallow sea, but occur wherever it is wet and were light is present. They formed many limestones which are found in other places within the deposits of the Precambrian. The Jordanian stromatolites, in contrast, must not have been produced in the sea, but rather in fresh or brackish water. Cyanobacteria have evolved a photo-system by which water is used as donor of electrons which than are used to produce molecular Oxygen. This process driven by the sun light results in the reaction $12 H_2O + 6 CO_2 = C_6H_{12}O_6 + 6 O_2 + 6 H_2O$. Thus water and carbon-dioxide from the air are synthesized to form sugar as basic material for other organic substances and oxygen. The oxygen may be released to the atmosphere and during the extremely long time of the Precambrian it eventually became sufficient to produce the Ozone belt in the higher stratosphere, which hinders hard rays of the sun to reach the earth surface. The invention of photosynthesis connected to the production of free oxygen is at least 2000 Million years old, perhaps even much older, and it has influenced the biosphere dramatically. Cyanobacteria conquered the whole world and produced organic food in masses until later some larger bacteria which devoured other cells, became the ancestors of the Eukaryota, detected in rocks of about 1600 Million years of age. The spreading of Cyanobacteria caused a slow change in the composition of the atmosphere of the earth by adding oxygen to it. Their activity changed the composition of sea water to containing more dissolved oxygen. About 1800 Million years ago deposition of iron oxide in the sea ended, which is thought to had been caused by purple bacteria, and for them free oxygen is a poison. Oxygen in the atmosphere changed the permeability of the atmosphere for ultraviolet light, which is destructive to life. It was reconstructed that about 1500 Million years ago about 20 % of the atmosphere was composed of oxygen, as it is today, but this assumption still has to be confirmed.

The tuffaceous beds next to the basal beds and covering them have a porphyritic texture containing crystals of larger angular outline in a fine greenish matrix (Fig. 7). The slates show massive appearance and brake into angular large slabs. Their texture commonly is that of laminated beds, often somewhat wavy as found in stromatolites. Fine cross beddings present in layers and volcanic bombs are scattered in the fine substrate. About 28 m of finely laminated, predominantly greenish slate are exposed. Angular mud clasts can be observed as they form when mud coated by cynobacterial mats dries, brakes into sherds and mud sherds are reworked by the water flowing across. 44 m of greenish, mostly thinly laminated slates follow also finely interlaminated in a stromatolitic texture (Fig. 8).

Fig. 7: Volcanic bomb with porphyritic structure as part of the tuffaceous Abu Barqa Formation.

Fig. 8: Sequence of tuffaceous slate of Abu Barqa Formation seen towards the southern Wadi Araba with crystalline base at lower right and ignimbritic tuffs on upper left.

On bedding planes ripples are preserved with ripple crest having a distance of about 3.5 cm from each other and with rounded symmetrical shape and straight alignment. Many impacts of small volcanic bombs have left their marks on surfaces as well as rain drops. Also mud cracks are present and in addition to straight elongate angular marks retracing the shape of ice crystals which grew in the wet sediment (Fig. 9).

Fig. 9: Surface of tuffaceous slate with volcanic bombs which slid on the smooth surface after having landed on the slippery top and with changing winds.

18 m of dark gray slate with marks and trail-like features on their surface follow. These are overlain by 20 m of green and gray slate with marks and ripples usually about 5 cm distant from each other and of slightly sinuous orientation. 24 m reddish and more rarely green slates follow which also have marks on the thinner beds. They represent a deposition of graded silts and mud. All these fine grained sediments in Wadi Abu Barqa Formation have been affected by the presence of cyanobacterial crusts. Thus casts of the bubbles of oxygen that formed during their photosynthetic activity are commonly preserved on bedding surfaces. They are distinguished from marks of rain drops by difference in shape. Rain drops leave impacts with a small hill in their centre, while the bubbles do not have a median hill. The presence of bubbles also had influence on the shape of mud cracks. Slippery and continuous mat surfaces served as gliding plane for pieces of pumice that had fallen onto them. These, sometimes, had been pushed by wind. The traces formed by the slipping pumice sometimes changed their direction when wind direction changed leaving a trail on the surface that resembles trace fossils or even has the shape of a flat tadpole- frog larva.

This sedimentary series is overlain by about 35 m of bedded tuffs. This series also contains some sedimentary layers which usually are finely laminated, and may show stromatolitic lamination and cross beds. Mud cracks are more commonly observed here than in the layers of the lower sedimentary sequence. These sediments also show signs of slumping and folding due to sliding on a slope. This is especially so in a sedimentary series of more sandy composition than observed below, as found just below the first Cambrian sandstones here forming a small hill in its outcrop on the base of these sandstones. The whole segment has been deformed into sliding folds indicating that this unit was moving on a slope. When this movement occurred, the sediment had been semi-consolidated since movement did not only deform these beds into folds of larger and smaller dimension but also movement occurred along the bedding planes leaving striations there. This later feature indicates that the sediment was partly dehydrated when it moved down the slope. A sill of andesite with large crystals in fine-grained matrix is found, all arranged in one direction, and still documenting its direction of flow during emplacement. It is exposed further up in the Precambrian succession in a dry valley that has been eroded into the Cambrian sandstones exposing their base behind the first outliers of this formation. Above the sill there are many more layers mainly composed of tuffaceous material, with a layer of fused material as is found in ignimbritic fused tuffs. These beds are representing an extended series of predominantly volcanic material a few hundred meters in thickness before being covered by Cambrian sandstone (Fig. 10).

Fig. 10: Slate of Abu Barqa Formation overlain by tuffs of ignimbritic character and further tuffs and Cambrian sandstones.

The depositional environment of Abu Barqa Formation can be interpreted as a lake in a caldera with partly inundating sediment surface and partly having its bottom falling dry periodically. Thus flat beds as well as slumps and impacts are explained. The caldera may have formed as collapse structure of the volcano that penetrated the surrounding crystalline environment. Water present in the lakes of the depression was not salty since not a trace of salt crystals or gypsum crystals has been found, while other traces are preserved quite well. Thus bubbles produced by cyanobacterial mats are documented; indications of rain drops are present, drag and tool marks, current stripes, erosive marks formed by currents in the water. Ripples of the size as formed by wind in shallow water or even in puddles of water are all in accordance with deposition under the influence of a periodical cover with shallow water (Fig. 11). The rarity of desiccation cracks on the surfaces which otherwise indicate that they have been exposed to the air, may be interpreted as a sign of relatively cold and humid climate. What can be interpreted as traces formed by ice growing in the muddy surface is not common though. The volcano was not far away and almost constantly active.

Fig. 11: Wind ripples and rain drop marks on the base layer of a bed of Abu Barqa Formation.

The sedimentary series measures almost 120 m in thickness from the top of the granite and its debris to the overlying deposits of tuff and ignimbrites above. The base of the tuffites filling the caldera is formed by granites and depressions between granitic hills filled by angular and rounded debris derived from the crystalline base and containing volcanic material. The slate was deposited in a subsiding basin and always near the surface of the water that periodically filled this basin. Mud cracks are rare in the lower series, while they become more common in the upper portion of this series, and in the sediment beds included in the mainly tuffitic and volcanic flow beds following above (Fig. 12). Tuffaceous layers are included in the sedimentary series and they can be traced for long distances without changes in their thickness, which is from a few centimeters to almost one meter. This indicates that the volcanic eruptions during sedimentation were common and represent a rather uniform rain of volcano-clastica onto the surface of the basin deposits (Fig. 13). Single volcanic bombs are also present, usually small with a size of only a few centimeters as maximum. They did not form deep impact craters, so that the original material was probably rich in gas inclusions (pumice) and thus light in weight. This also explains why these volcanic bombs have subsequently become compacted and flattened during diagenesis.

Fig. 12: Higher part of Abu Barqa volcanic series with the broad gray sill intruded into the tuffaceous and ignimbritic beds above and below and truncation surface with Cambrian sandstones on top of it with clear erosion angle of discordance.

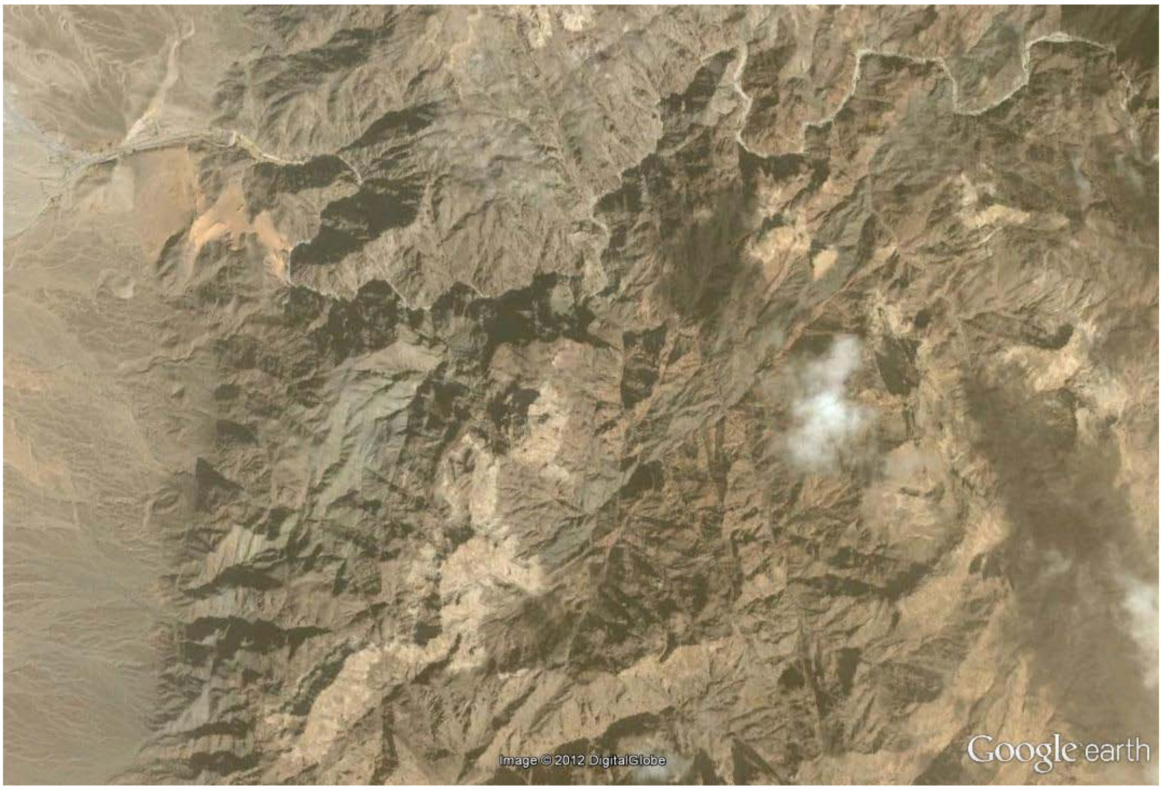

Fig. 13: Wadi Abu Barqa as seen in Google Earth with the dyke in the central part of the picture,

The Saramuj Formation is not found in contact to the Wadi Abu Barqa Formation. While the first outcrop is exposed near Ghor Safi, the later lies about 80 km south of it near Gharandal. The Saramuj Formation is exposed at the ancient monastery of Lut that has been excavated from these rocks and lies in the slope above the town of Ghor Safi. The composition of the sediments of Saramuj Formation appears to be less altered by diagenesis than the rocks of the Wadi Abu Barqa Formation, but they are usually of much coarser grain size (Fig. 14). Its composition is of the debris of erosion of predominantly volcanic rocks and their crystalline base. The Saramuj sequence was inclined with about 15° and eroded to a hilly landscape when deposition of the Cambrian sand began. About 300 m of Saramuj Formation are exposed, without the base seen and with the tops formed by an angular discordance to the Cambrian beds. The beds of Saramuj Formation had been transected by many volcanic dikes, which end at the contact to the Cambrian and had been eroded prior to the deposition of these sandstones.

Fig. 14: Saramuj channels hold some huge boulders which have been transported here during catastrophic flood events (the foto has been provided by Olaf Elicki, who stands at the base of the boulder).

Saramuj consists of arkosic substrate with conglomerates arranged in channels. It represents a mix of weakly rounded and well rounded pebbles and boulders. The quartz grains formed by disintegration of the granite have in part not been rounded, and also small angular greenish clasts of volcanic sediment are common. Cross bedded layers often show graded bedding. Granitic boulders are often very well rounded and of different sizes. Some channels have about half of the pebbles consisting of granite, the other half of different other rocks, mostly of volcanic nature and greenish color. Pebbles can also consist of ignimbritic volcanic material and bubble-basalt. Slates are usually of more angular flatter shape. Between the larger pebbles narrow thin sand filled channels have formed when less water transported finer material in meandering little streams between the pebble strewn riverbeds. A large channel of about 10 m in thickness contains up to 2-4 m wide rounded boulders. The orientation of boulders in the channels is present with imbrications pointing to a current towards the south.

The whole sequence of fluviatile to fanglomeratic sediments is transected by many dikes of 1-10 m in thickness and of diabasic composition with degassing bubble structure (Fig. 15). Most of these dikes are oriented in about S-N direction, but also vertically to them dikes are present, but are usually less wide. The dikes can have large plagioclase crystals which are oriented parallel to each other and parallel to the orientation of the dike. Also a larger intrusion is present which caused contact metamorphosis. Pebbles eroded from the Saramuj exposure are fresh and with smooth surface, while those close to the former Cambrian surface became decomposed.

Fig. 15: Saramuj Conglomerate is transected by diabasic dykes (Foto of Olaf Elicki)

Poorly rounded pebbles and boulders represent material that was transported for short distance by fast flowing rivers. No striation was noted on boulders, thus transport with ice is not documented. But the area of erosion of this material cannot have been far away and it should have been a mountain with granite as well as volcanic rock exposed and freshly eroded. Its position lay in the NE or N of the present area. Because coarse and fine grained quartz rich and volcanic components had not become separated from each other, these materials have not been transported very far and not been sorted by weight. The exposed gravel canals have a direction of about North to South and the gravel orientation would suggest a flow from the north in a southern direction. The large components included in these canals filled with gravel are evidence of source rocks not far away from their deposition and the distance to the rugged mountain to the North. Similar deposits have been noted from the Red Sea Hills on the western side of the Red Sea which could have been derived from the same mountain range. Its presence is a riddle that does not appear in paleogeographic reconstructions. Its position would lie in an area, from which later during the Cambrian the sea of the Prototethys transgressed onto the African-Arabian part of Gondwana.

In the Saramuj Conglomerate next to several types of pebbles derived from the crystalline basement it is composed also of volcanic debris with a wide range of compositions. The conglomerate had been intruded by a dioritic magma which was dated as being about 595 Million years old. It is overlain by Cambrian sandstone with a clear unconformity developed between both units. But it also appears to have been intercalated with sandstone similar to the Cambrian sandstone above. Since the beds of the Abu Barqa Formation have no contact to the Saramuj it is an unproven assumption that Saramuj is older than the Abu Barqa series, in part based on rather doubtful age dating. In the contrary, it may be possible that pebbles of volcanic rocks contained within the Saramuj Formation have been eroded from a similar sequence as that holding the Wadi Abu Barqa Formation. From the subsurface in northern Jordan about 1000 m of gravel were recognized underlain by volcanic deposits. It appears that the rift system resulting in the deposition of the Saramuj congomerate continued to NE Syria.

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2. Paleozoic of Jordan

Cambrian and Ordovician in Jordan

The Cambrian in Jordan consists predominantly of sandy deposits which were carried here by wind, rivers and currents of shallow seas. The quartz sand has predominantly been eroded from the crystalline basement of the old Gondwana continent in the south (African-Arabian Plate). A combination of tectonic and climatic changes may have resulted in a major global transgression at the early Cambrian, around 530 Ma ago. The Precambrian surface of Jordan was drowned by this Cambrian "sand-sea" (Fig. 16). In the North an ocean that may be called “Prototethys or Paleo-Tethys” extended onto the margin of the continent with a shallow sea which deposited sandstone and some limestone. Locally the sandstone is rich with trace fossil and the limestone consists predominantly of skeletal fossils of animals which lived near mid-Cambrian time about 510 Ma ago. That rich fauna allows a good view into the diverse life that was present in the shallow sea at that time and also allows a view onto the quite different character of the organisms in comparison to those living today.

Within the early Cambrian the whole of Jordan had its position in a shelf region on the marginal African-Arabian plate. When it slowly subsided, sediments coming from the South kept the land just above or at about sea level with the open sea in the North. This general character of the shelf area persisted for a long time and ended only with the large orogenies which occurred to the West. The first of these mountain formations, the Caledonian one occurred between the end of Ordovician and the Silurian and had only little impact on the geological set-up on what afterwards became Jordan. But the second, the Variscan or Hercynian orogeny between late Devonian and the end of the Carboniferous, coincided with times of predominant erosion in Jordan and extensive rate of truncation. During the later times the supercontinent Pangea formed in which several former continents fused with each other to form one continent. During late Ordovician and again late Carboniferous to the early Permian at some intervals of time the sea level dropped periodically due to the fixation of water in the ice of glaciations on Gondwana continent.

Fig. 16: Cambrian sandstones at Wadi Rum with Precambrian peneplain base and alluvial valley filling, succeeded by Salib Formation and the well banked Umm Ishrin Formation forming the steep flanks and Disi Formation with white rounded shapes at the top.

Basal Cambrian sandstones in Jordan overlie Precambrian rocks of quite different characters. In the SE of Jordan from Wadi Gharandal, to upper Wadi Yutum and in Wadi Rum area it overlies the old crystalline basement that was eroded to form an almost flat regional peneplain. On its surface quartz pebbles are found among the coarse grains which formed predominantly by physical erosion on the crystalline base. These were more or less washed and sorted, at first to form a sand of angular quartz and feldspar grains. This process washed out fine products of erosion and washed them off as suspension in the water and left the coarse grains, predominantly quartz and feldspar, which often resulted in a change of color from brown and gray to lighter color. The sandstone above the crystalline base was deposited by rivers flowing from the south on an almost flat landscape and the sea coming from the north with conditions of a dry climate so that feldspar was not destroyed. Near Wadi Rum (Ram) the quartz pebbles of the old erosion surface may be wind facetted. This indicates that a wind-blown plain was the base of deposition for the brownish sandstones of the Saleb Formation.

North of Gharandal area in the mountains on the eastern side of Wadi Araba Cambrian sands covered a hilly landscape composed of volcanic deposits of Abu Barqa Formation with angular unconformity (Fig. 17). The Precambrian beds display a clearly different digenesis to that of the sandstones and have their shale deposits transformed into slate. Cambrian sandstones, therefore, covered the Precambrian series with a clear erosion unconformity (Fig. 18). The sediments of Abu Barqa Formation were weakly metamorphosed, deformed and eroded. It can be assumed that more than 100 m of Abu Barqa rocks were eroded away, probably much more. The unconformity displays the Precambrian rocks inclined towards the south and southeast in the eastern area of their exposure. The Cambrian deposits, in contrast, are almost horizontally oriented, quite in the position they had at the time of their deposition. The rugged hilly landscape covered by Cambrian sandstones displays rock strewn slopes as well as former valleys with rocks rounded by the action of water in their base (Fig. 19).

Fig. 17: Inclined tuffitic slate and volcanic deposits of Abu Barqa Formation overlain by Cambrian sandstone deposited onto a hilly landscape, view to the east from the top of the Abu Barqa Mountains.

Fig. 18: First Cambrian sands are deposited in dunes onto Precambrian Abu Barqa (Jörg Schneider as scale).

Fig. 19: Pebble-bed of a creek between hills of eroded Abu Barqa Formation, covered by Cambrian Sandstone

Along the foothills of the escarpment of the eastern side of the southern Dead Sea near Ghor Safi and at the mouth of Wadi Hasa the coarse grained Saramuj Formation displays an eroded surface that became weakly inclined before it was overlain by Cambrian sands. Saramuj conglomerates have no obvious differences in diagenesis in regard to the Cambrian sandstone above, but volcanic dikes transecting the Saramuj do not continue into the Cambrian sands.The first Cambrian deposits of Salib Formation consist of fluviatile coarse sands with gravel filling former channels. The pebbles composing the gravel consist of quartz and rounded volcanic rocks of the type found in the ignimbritic beds at Wadi Abu Barqa. Still within the basal sandstone here one layer is totally bioturbated, thus documenting that marine conditions were intermittently present. When sea water covered the sands endobenthic animals burrowed and destroyed the formerly present cross bedded structure. On land, at that time, no bioturbation occurred since no higher organism lived here which entered the ground. Plants had not yet appeared and therefore no roots penetrated the deposits, and only near the end of the Ordovician began their evolution from green algae. No land plants on the surface of the earth held or stabilized, at that time, the weathered rock. Only mats of cyanobacteria formed on wet surfaces and could stabilize the sediment as had been the case in the Precambrian sediments of the volcanic series of Abu Barqa Formation.

In Abu Barqa area the sandstones covered a more or less rugged landscape, first by wind-blown sand, later by sand carried by rivers and rarely by the sea, but by the end of the early Cambrian the sea came from the North and covered most of Jordan for extended times (Fig. 20). By that time the different morphologies over which the Cambrian sands were spread by rivers or wind created such a flat and level plane within the deposition of the first 100 m of sand that a shallow sea could spread over its whole surface. Abu Barqa hills present evidence for that marine excursion by a pipe rock layer (*Scolithos*) that can be correlated with late lower Cambrian and early middle Cambrian calcareous deposits exposed near the Dead Sea. The morphology of the surface of land in Jordan during the first deposition of Cambrian Sandstone, thus, appears to have had no hills higher than 100 m above sea level.

Fig. 20: View from Abu Barqa Mountains to the North. Cambrian sandstones deposited on the flat crystalline base with locally only a thin basal layer of volcanic debris between it and the sandstone.

The depositional environment of pipe rock sandstone, with the trace fossil *Scolithos,* is a shallow water environment near the shore with high energy environment (Figs. 21 and 22). Here worm-like animals formed vertical burrows used as single-entrance dwelling burrow (Domichnia). The tubes in the sand were constructed by worms or worm-like organisms which lived very close to each other and were suspension feeding. *Scolithos* is one of the more common ichnofossils of shallow marine deposits. Lophophorate phoronids (a sort of arm bearing worms) or tentaculate, crowned polychaetes representing annelid worms are likely producers. It is known from other areas that in early Cambrian these animals existed and they probably functioned very much like their still living relatives. In the case of Phoronidae, tubes are coated with chitin and the head bears more than 100 tentacles which catch food, with only few species (about 20) today living in the sea. Among the Polychaeta several groups of these segmented worms have a tentacle crown and their body bears bristles with which they climb in their burrow that may have walls coated by mucus or a chitinous substance. Preserved soft part animals of both types are known from the Cambrian of the Canadian Rocky Mountains (Burgess Shale) and from China (Chengjiang Formation). Suspension utilized by them probably contained many algal cells of the Plankton present in the shallow water of the sea. The *Scolithos* layer can represent the time equivalent to the marine deposits found in the Cambrian of Jordan north of the Wadi Feinan (=Finan) area. It is called Burj-Limestone or Wadi Nasb Limestone and is of late early to early middle Cambrian according to the trilobites found in it.

Fig. 21: *Scolithos* sandstone in the lower part of the Cambrian Sandstone at Abu Barqa Mountain.

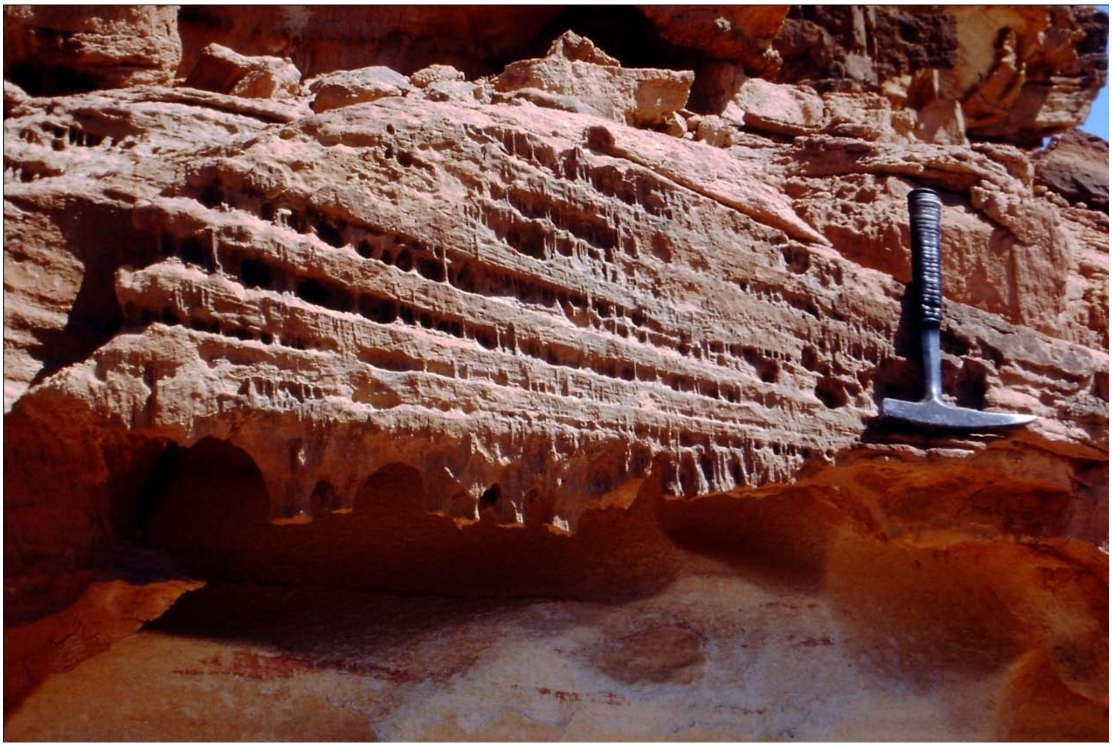

Fig. 22: *Scolithos* burrows in cross bedded sand give evidence for their formation in a channel near the beach.

The almost planar unconformity in Wadi Rum area is overlain by the Saleb Formation (=Salib) also called Quweira Sandstone (lower) with a thickness ranging from 30 m at Wadi Rum to about 60 m and more in the north of it for example in Wadi Hasa to

Wadi Tayan. The begin of sedimentary deposits on top of the physically eroded and loose sand, formed from the metamorphic rocks is well documented by sorting, which carried fine brown material of finer grains away as suspension in the water that reworked the soil.

Well preserved *Cruziana* trails formed by trilobites are found about 30 to 40 m above the Precambrian base near the road to Wadi Rum. Here the lower Quweira Sandstone (Saleb Formation) near the Desert Highway consists of a basal conglomerate, and, banked arkosic sandstone is overlain by the upper Quweira Sandstone (Umm Ishrin Formation) consisting of brown sandstones up to 350 m in thickness. Umm Ishrin Formation consists of sands arranged in about 25 cycles with relatively coarse grained sands with quartz pebbles in the lower part and finer sand and sometimes silty sand above. Here, locally, many with trace fossils are preserved in the upper finer part. The coarse basal unit, in a cycle may hold channels which are filled with non-mature arkosic sand as that composing the Saleb Formation. This documents that during the cyclic deposition of Umm Ishrin sandstone lands providing arkosic sandstone were not far away. Also deposition of sand in the bulk of each cycle was usually rapid so that the wandering ripples still contained so much water that right after their deposition the water left and deformed them forming quite regular cushion shapes (reclining ripples). The commonly occurring brown crusts in the fine sandstone represent the deposits of dried playas and may be the result of former groundwater tables and have formed within the sand.

Cruziana is produced by trilobites burrowing their way below sediment surface, *Rusophycus* represents the resting trail of a trilobite, first encountered only about 30 m above the base, and found locally within most of the cycles of the Umm Ishrin Formation (Fig. 23).

Fig. 23: Trilobite resting trails (Rusophycus) from the Cambrian sandstone of Umm Jafna in the canyon of river Hasa (picture from Olaf Elicki).

Trilobite trails are common on some bedding surfaces of the Cambrian sandstone and also in the Ordovician sandstones. Remains of their skeletons are found in the limestone of the Burj Formation. The intercalated sandstones of that formation commonly preserve their trails. These animals can be considered as characteristic to the Paleozoic, and their diversity reached a peak in the Cambrian. Trilobites resemble somewhat modern isopods such as they survive now in creeks in Jordan and along the shore of the Gulf of Aqaba. But Trilobita and Isopoda are not related to each other, except that both represent members of Arthropoda. The trails of isopod crabs produced when the animal moves along the surface of soft bottom sediment can be very similar to *Cruziana*. Trilobites became extinct at the end of the Paleozoic.

Arthropods such as trilobites have an external skeleton and when growing they exchange the smaller older one carapax with a larger newer one (molting). The old skin, or exuvium, does usually not consist of one piece, but of several parts. The tail part or Pygidium consist of several fused segments and often has characteristic shape that may allow the determination of the genus. More commonly it allows only a general placement in a group of related trilobites. The central part of the skeleton, formed by single elements (Pleura) usually detaches into these during or right after molting. They are usually of no use in determining a species (Fig. 24). The head provides most information and is usually characteristic to the species. But when molting (shedding their skin), the trilobite leaves the old skeleton through a suture that splits the head shield along a line often separating the sides with the eyes from the median part. The shape of this suture, as well as the characters of the median part (Glabella) has to be known in order to be able to determine the species. Skeleton composition in the fossil is phosphatic apatite and was, originally prior to diagenesis, chitin with some calcite. Thin sections of Cambrian limestone from Jordan usually display such skeletal remains. Trilobites evolved rapidly and the encountered species are good biostratigraphical markers. Species of *Enixus* (*Palaeolenus), Kingaspis* and others were determined and described. The organization of their body and here especially that of the appendages (feet), suggests that they were collecting detritus for food, and plowed through the sediment in search for that, producing the *Cruciana* trails. When they rested in a place they left the *Rusophycus* track.

Fig. 24: Central part of the head shield of the trilobite R. blanckenhorni from Wadi Uheimir (from Olaf Elicki). The head is incomplete with the sides having detached during molting.

Not only trails, which most probably were produced by trilobites are found but also such that have a different character and resemble the trails which nowadays are produced by the horseshoe crab *Limulus*. It belongs to the Merostomata of the Chelicerata, and that group, distantly related to spiders, was present with several species in the Cambrian. Additionally, a lot of further traces of arthropods and those related to worm-like and sea-anemone-like organisms, occur.

Limestone beds occur after 100 to 120 m of sand were deposited, and the limestones found in a side branch of Wadi Tayan (Wadi Uheimir) is not very different from that exposed at the road north of the mouth of Zerqa Ma'in into the Dead Sea and as exposed in the canyon of Wadi al Hasa. Here at the Dead Sea the Cambrian sequence is up to 690 m thick and is well exposed in the area of Zerqa Ma´in. In the area of Wadi Finan, the Burj Formation consists in parts of silty and sandy layers and some intercalations of dolomite beds with some lamination of stromatolitic type, some desiccation cracks and rock salt (halite) pseudomorphs. Here deposition took place in shallow intertidal environment with dry climate. The sea had come from the northwest thus time equivalent beds further north were deposited under more fully marine conditions. Here the Burj Formation can been divided into three members, a lower Tayan Member consisting of sand and silt beds often with bioturbations, the central Numayri Member with limestone and some glauconitic greenish sand, and the upper Hanneh Member consisting predominantly of sand with trilobite trails and other trace fossils.

The limestones include layers with oncoids and cross bedded oolites. Ooides are round calcareous grains of sand size with concentric construction. A nucleus of some kind, often a fragment of shell are found coated by several layers of carbonate, mostly as modification of calcite under the influence of cyanobacteria. Their mode of formation has not changed up to modern times and thus it has been studied in detail, especially on the Bahama Platform near the American East coast. In clear shallow water sand is transformed into ooidal grains and these are washed around by currents and may become piled up to form dunes or be deposited near them. Their occurrences in some beds of the Burj limestone which are exposed in different places along the Dead Sea are evidence for a similar environment as that of the modern Bahamas. Oncoids have a similar construction but are larger than sand grains. They also formed by the activity of Cyanobacteria but around larger grains, and they form where particles are rolled around by currents in well illuminated environment. Nowadays such oncoidal sediments often form near wave washed beaches of lagoons and fresh water lakes, the Cambrian ones clearly formed in the sea.

In Wadi Uheimir of Wadi Tayan some limestones have “birdseye structure” representing characteristic deposits formed in carbonate mud as is found in a lagoon (Fig. 25). Their formation can only in part be studied in the modern environment, since the result is seen only after cementation and some diagenesis. Within a shallow, well illuminated quite environment of standing water carbonate mud can be coated by a cyanobacterial crust which produces oxygen during its growth and carbon-dioxide and or hydrogen-sulfide gas during its decomposition. The bubbles thus formed can move through the mud until early cementation solidifies it. Into the cavity of the bubble coarser cement grows filling them with clear calcite. These are the “birds-eyes”. The mode of formation did not change much from the Cambrian until now and similar lagoonal limestones have been formed in Jordan also in Triassic and Cretaceous deposits.

Fig. 25: Wadi Uheimir with the carbonate deposits of Burj Formation with some beds of limestones rich in fossils.

During the Early Cambrian a revolution of life occurred during which many of the animals, which still have relatives, for example living in the Gulf of Aqaba, appeared. Quite different groups distinguished clearly by the organization of the soft body, such as mollusks with calcareous external skeleton (Helcionellida), brachiopods with phosphatic and calcitic shell, arthropods with chitin as building material, echinoderms with internal calcareous skeleton and others appeared suddenly. It is still a riddle what caused them to invent their hard parts more or less at the same time, near the base of the Cambrian. The rich fauna encountered in the Burj Formation of Jordan lived already some 25 Million years after that event (Figs. 26 ad 27). They are encountered in the deposits of late Early Cambrian to early Mid-Cambrian from the area at the northern end of the Dead Sea near Wadi Zerqa Ma'in to the area of Wadi Tayan and Wadi Fifa to the south of the Dead Sea. The more easily recognized fossils are represented by brachiopods, trilobites and hyoliths. Small sized ones can be extracted by dissolving the limestone and by thin – section, and here silicious sponge spicules and echinoderm skeletal elements are common.

The small shells of Helcionellida which can be extracted from the limestones are members of the Mollusca, but cannot be placed in one of the classes of these animals, even though they resemble limpet-like gastropods. All we know about their early shell formed by the youngest individuals does not fit and thus their first shell differs from that of all known gastropods. But a torsion of the body as in gastropods cannot be documented for helcionellids. It has also been reconstructed that Helcionellida evolved into the first Cephalopoda during mid Cambrian, while first Gastropoda are known only from Ordovician onwards. Also the Bivalvia might have developed from Helcionella-like ancestors, but differ from these by developing two shell valves during their ontogeny. Those Helcionellida known from the Jordanian Cambrian, up to now, have not been preserved well enough to help to solve that riddle.

Fig. 26: Cambrian marine deposits of Burj Formation with carbonates at the shores of the Dead Sea as in 1979, just to the North of the mouth of Zerqa Ma'in River.

Fig. 27: Part of the carbonate section of Burj Formation with nodular limestone formed by strong bioturbation at the side of the road along the Dead Sea just north of Wadi Zerqa Ma'in.

Brachiopoda of two types occurred. The group of them with a calcareous shell and two valves of different size of the Articulata is represented by *Trematobolus.* Its shell is thick and up to 17 mm large and it lived in great numbers near the shore, now common in Wadi Tayan and its side branch Wadi Uheimir. The smaller valve has a pair of tooth-like small nodes at the interior side which can be interpreted as denticles of an articulation mechanism. The nodes are not connected to distinct hinge sockets, which is in contrast to many modern brachiopods. A pedicle groove is developed on the larger valve. Muscle scars on both valves document their function as found in modern brachiopods with a pair of muscles to close the valves and another one to open the again. Among the animals found in the Gulf of Aqaba small brachiopods are found which in all essential features function just in the same way as the *Trematobolus*. The modern species of *Argyrotheca* the small animals (only about 3 mm wide shell) are attached with their pedicle, a foot like expansion of the soft body that extends through a hole in the larger valve, to corals or other hard substrates, and the shell is held free in the water. Thus the spirally coiled arms held on the smaller valve can pump water with their cilia and also select particles from the water. These are transported by cilia along the arms to the mouth. As in the Cambrian relatives the shell is composed of calcite.

The conical shell of *Hyolithes* belongs to an animal that lived within the shore zone and carried a shell of up to 30 mm in length and 4 mm in width composed of calcium-carbonate with the narrow posterior part of the slender cone closed off with septa. It has been interpreted to represent a tube worm, but of a kind that has no living counterpart (Fig. 28). The shells of *Hyolithes* may be so common that they compose some layers which were present along the shore of the former sea as can be noted from the northern exposure of the Dead Sea to the area SE of Ghor Safi near the mouth of the Wadi Al Hasa, within the Wadi Al Hasa, above the Saramuj conglomerate east of Ghor Safi and at Wadi Uheimir in Wadi Tayan. Commonly several empty shells are stacked into each other, sometimes they are preserved with the calcareous lid still in place. That operculum resembles that of the modern tube worm *Spirorbis* (Annelida, Polychaeta) which is much smaller and can also be encountered attached to hard surfaces as well as algae in the shallow sea at Aqaba.

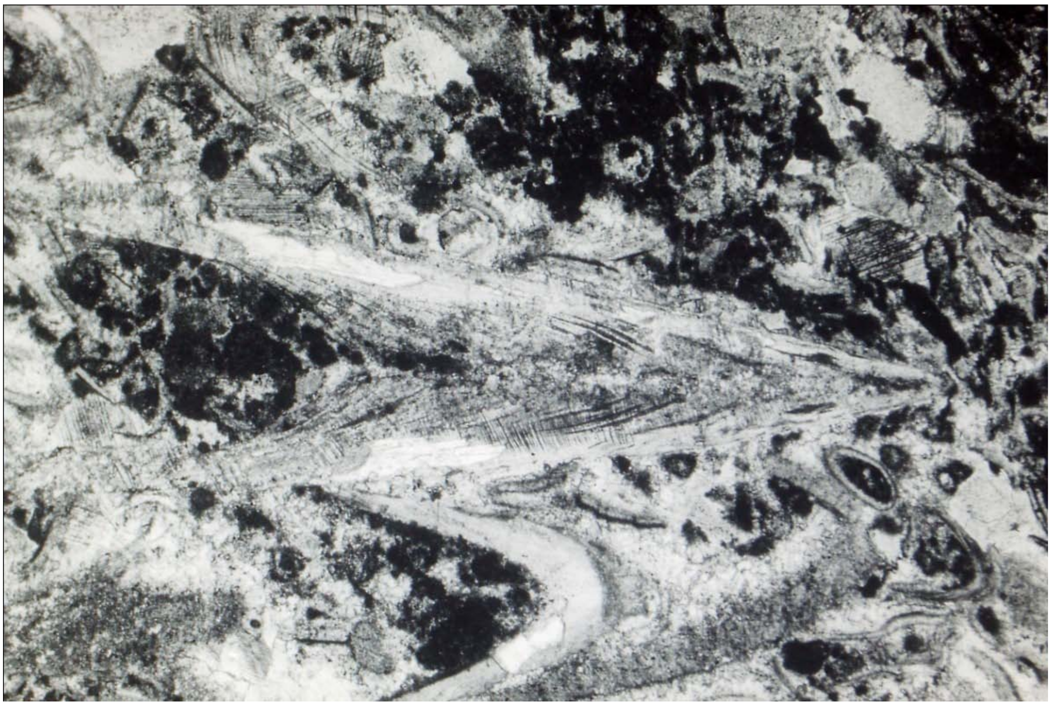

Fig. 28: Thin section of the limestone with Hyolithes kingi, also present are echinoderm skeletal particles, sections of trilobite skeletal remains and coated grains.

Echinoderm skeletal elements are very common in some limestone layers and are well recognized by the reticulate composition in calcite. This type of skeletal composition is characteristic to the Echinodermata from Early Cambrian to those of the modern Gulf of Aqaba. Each individual part of the skeleton thus consists of a calcitic frame in which the crystals are all arranged as if in a single crystal. During early diagenesis it usually is exactly what it grows into, a single calcite crystal. In case a thin coat of pyrite forms within the skeleton on the walls of the pores before that happens, this internal structure can be seen later in the single crystals, as is commonly the case, in those from the Cambrian of Jordan (Fig. 29). The producer of the skeletal remains from Burj-Limestone is less well known due to the decomposition of the skeleton. They belong to the Edriasteroidea and Eocrinoidea and among them might be a precursor to the Crinoidea among the Echinodermata, and also the modern crinoids *Antedon*, that lives among the corals of the reef in Aqaba. As its Cambrian relative, *Antedon* disintegrates into many small skeletal particles soon after death.

Sponge needles of silica sponges as well as of calcareous sponges are present. The characteristic sponges of that time, the Archaeocyatha are quite exceptional fossils in Jordan. But sponges belonging to the large and diverse group of especially the Hexactinellida and less to the Calcarea are present. They were and are feeding by sucking water through the ciliated cavities of their body which is held in shape and protected by the skeleton consisting of needles. Small food particles are taken up individually by the cells coating the interior chamber (Choanocyta). Sponges are animals which have organized their body quite differently from others. They support their body with organic fibers and mineral needles, sometimes with additional calcareous deposits between them. Different species may form low crusts, larger bodies of no specific shape, or species with specific shape usually composed of many individuals and sometimes up to more than 1 m high or wide. Some also consist only of a single individual, as is the case with the Archaeocyatha. Water is usually expelled through one or several larger canals, and is thus blown away from the animal.

Trace fossils which resemble the trail produced by the coelenterate *Ceriantharia* which lives on sandy sea bottoms are also present. This sea anemone has its home within the sand and extends its soft body over the sand surface to hide into the sand whenever threatened. The wall of the home-tube is coated with mucus. When sand is added to the surface the sand anemone balances the difference by adding sand to the base of the tube. The resulting burrow structure consists of a sand filled anterior vertical part connected to a laminated base. Exactly such burrows were noted in the sand intercalated with the limestones near the Dead Sea. The presence of *Cerianthus*-like coelenterates in the Cambrian can be assumed as likely since, during the following Ordovician, from soft-body sea anemones of similar construction the first stony coral developed by secretion of a calcitic skeleton to support their body walls (*Bergaueria*).

Fig. 29: Burj Formation as it is exposed near the southern Dead Sea at a locality with coelenterate tracks.

The Burj Formation overlies Saleb Formation and transition is well exposed for example in the canyon of Wadi Hasa. Along the foothills at the eastern side of the Dead Sea the Burj Formation contains limestones which bear many fossils. They contain remains of some of the characteristic marine animals of the time. It is about 190 m thick and consists predominantly of limestone, sand and silt in composition. Its age is Late Lower Cambrian to Middle Cambrian. The upper portion is the Umm Ishrin Formation with sandstones of more than 300 m in thickness which grade into the sandy Ordovician of Disi Formation in south Jordan (Figs. 30 and 31). At the top of Disi Formation marine shelf sands of the Umm Sahm Formation appear. Thus, it has been reconstructed that the Arabian Shield was uplifted three times, first connected to the deposition of Saleb Formation, second with Umm Ishrin Formation and again in Disi Formation during the Ordovician as noticed within the alluvial deposits in southern Jordan.

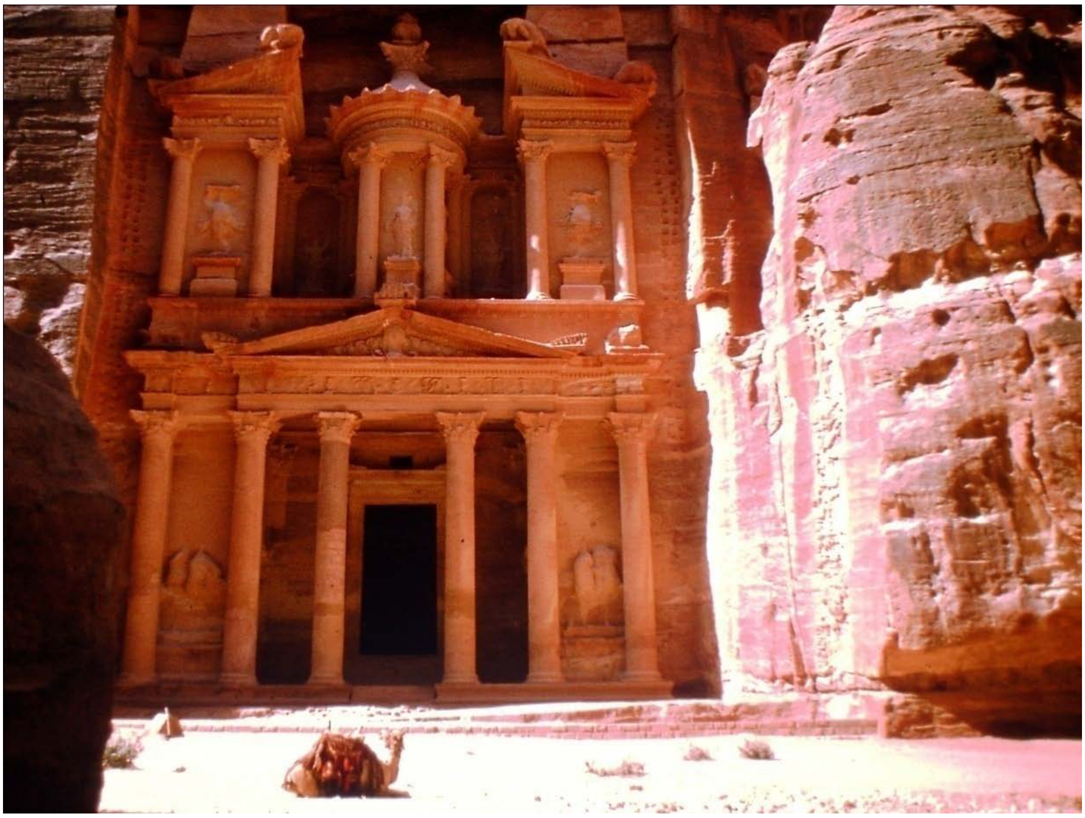

Fig. 30: The famous Nabatean Treasury at the end of the Sik forming a deep canyon in the Cambrian Sandstone at Petra is carved from Cambrian Umm Ishrin Formation.

Fig. 31: At Petra (Beida) the Cambrian sandstone of Umm Ishrin Formation is overlain by sandstones of the Ordovician Disi Formation with more rounded erosion and Cretaceous deposits in the background- view towards the east.

Cambrian sandstones are overlain by Late Permian sands and soils east of the Dead Sea and by Early Cretaceous Kurnub sandstone further south, while near Petra Ordovician sands follow, and in the SE of Jordan and east of Wadi Rum and Disi, sandstones of Ordovician to Silurian age cover Cambrian sandstones. In Um Bogma area of Sinai, Early Carboniferous shale, fossil-bearing marls and limestones overlie the Cambrian sandstone.

In South Jordan early Paleozoic rocks are represented by predominantly sandy deposits which are very well exposed in the slopes of the mountains on both sides of the sand filled ancient canyons of Disi on the road to Aqaba between Quweira and the begin of the Wadi al-Yutum and the east of Disi. Further to the east the approximately 400 m of Cambrian sandstone are overlain by the Ordovician deposits composing approximately 700 m of sediment thickness. Further north from Wadi Faynan in Wadi Hasa to the eastern slopes of the Dead Sea between the coarse base of Saleb Formation and the finer sands of the Umm Ishrin Formation, limestones and trace fossil-rich sands of Burj Formation are found intercalated and in thickness of the section increases to approximately 700 m.

Ordovician and Silurian of Jordan and possible composition of the now missing younger Paleozoic deposits.

Ordovician deposits are exposed along Disi, Wadi al Hiswa, Sahl Umm Tarifa to Wadi Batn al Ghul in southern Jordan and can be distinguished into the Formations Disi-Ram (more than 200 m of sandstone), Umm Sahm (about 220 m of sandstone), Hiswa (about 50 m of shale and sand), Dubeidib (about 85 m of sandstone), Tarifa or Mudawwara (about 140 m of predominantly sandstone), and ends with Batra shale that includes the boundary to the Silurian. Above follow Cretaceous fluviatile deposits which can and have been locally included as Ammar Formation. While the Disi Formation is exposed in the west just below the Cretaceous deposits of the Ras en Naqb, the succeeding younger Ordovician deposits are covered by younger beds to the east and Batra Formation is exposed only near Bat al Ghul near the old track of the Hedjaz railway. Thus with exception of part of Disi Formation most of the Ordovician sequence had been eroded below the western Ras En Naqb and near Petra when Cretaceous sedimentation began.

During the Ordovician Gondwana drifted so far to the South that by the end of the period the continent included the South Pole. This migration is connected to a shortening of oceanic crust and its subduction. During this period for example the Iapetus Ocean (Paleo Altantic) was closed causing the Caledonian orogeny which occurred predominantly in late Ordovician and Silurian time and resulted in the creation of the Laurussia continent (Old Red) that can still be recognized in the mostly crystalline rocks of the Canadian Shield and the metamorphic base of Scotland and Scandinavia. In Jordan this mountain building (orogeny) left no imprint in the deposition to be recognized. Sediments were predominantly quartz sand derived from the Paleao-Gondwana Continent in the south and deposited predominantly on the bottom of a shallow sea coming from the North.

Within the late Ordovician, at the Ashgill about 440 Million years ago, glaciers covered parts of Palaeo-Gondwana in the Hirnantian glaciation. Their impact is recognized on rocky land surface that was striated by ice moving over it. Diamictites and tillites are known from Saudi Arabia and may have partly been derived from glaciers located in central Africa and transported by way of a fluvial drainage system. Glacial deposits are also known from North Africa (Libya to Morocco). Scratch marks and grooves on the bed rock were formed when ice with rocks frozen into it migrated, away from the area in which the glaciers grew in thickness, towards lower land and on their way scraped the ground. Glaciations and deposition of much ice on the continent was connected to a strong fall of sea level because the water forming the ice had been part of the ocean-water before. When the glaciers reached the sea, ice bergs drifted off and melted on their way releasing the stones and the sand included in them. The marine deposits (tillites) resulting from such type of sedimentation have the characteristic marks of drop stones with deformation of the layers on the sandy bottom caused by the rocks which were released from the ice. Such sediments which formed in late Ordovician time are known from North Africa, and also from mid Europe; for example near Prague in the Czech Republic, but not from Jordan.

A part of Palaeo-Gondwana that is now in Mid Europe was recognized for example in East Germany and in the Czech Republic. It has detached from Gondwana after the Ordovician ice age which lasting about 0.5 Million years, was relatively a short time. These fragments of the continent detached from Gondwana and migrated during Silurian and Devonian time towards the North as a result of the spreading of a new oceanic crust between Palaeo-Gondwana and these former continental parts of it. They thus became islands consisting of continental crust, called terranes. As terrane they moved towards the Old Red Continent, as former oceanic crust was subducted and new ocean crust formed. The Saxothuringian Terrane and Bohemian Terrane (known as Barrandium) moved to the North until the ocean crust between them and Laurussia was reintegrated with the mantle (subducted) and these terranes fused with

Laurussia (Old Red Continent) during mid Devonian. The fusion of crusts is part of the Variscan Orogeny (Hercynian Orogeny) that had left no recognizable impact on the sedimentation in Jordan since sediments of that age are not recognized here, and at about that time the area was uplifted and much sediment eroded.

In Jordan the sequence of Ordovician to Early Silurian deposits is well exposed in the desert in the SE and well exposed in the slopes between the town Disi in the west and the remains of the former Hedjaz Railway in the east along the road to Mudawwara and to Saudi Arabia. Predominantly, sandstones are exposed very extensively along Disi, the Wadi Hiswa east of it and the following Sahl Umm Tarifa to Wadi Batn al Ghur in the east composing approximately a rock column of 700 m in thickness.

The series can be dated by the help of the organic microfossils acritarchs and chitinozoa, and locally by graptolites to range from Arenig to the end of Ordovician into Silurian. Chitinozoa are hollow club like in shape with or without spines and acritarchs are round, often spiny microfossils which resemble the cells of some modern unicellular planktonic algae. Their outer wall consists of organic material which can resist many changes in rock composition (diagenesis) and be extracted from fine silicoclastic material (silt and shale) by dissolution of the rock with hydrofluoric acid, similar as is the case with pollen and spores, which start to appear only by the end of Ordovician.

The basal Disi Formation composing more than 200 m of sandstone is interpreted to hold the boundary from Cambrian to Ordovician. This sandstone is composed of quite pure quartz sand with layers of quartz pebbles often forming the base of each cross-bed or as conglomeratic intercalations within larger cross-bedded units. Only in a thin intercalation silt and sand layers are laminated and have provided trace fossils as produced by trilobites (*Cruziana*). Also traces produced by other arthropods, possibly belonging to the Merostomata, have been recognized here. Disi Formation sands are well sorted, white and their erosion produces rounded shapes quite distinct from the brown and harder sands of Umm Ishrin Formation below and even darker brown Umm Sahm Formation above. On Jebel Umm Ishrin at Wadi Rum and several of the neighboring mountains to the east this change in color and shape is well observed. The Disi Formation holds the deposits in large channels and probably formed predominantly in the shallow sea. The sand and quartz pebbles composing Disi sandstone indicate a source of more mature and bleached sand than present in the Umm Ishrin Formation below and the Umm Sahm Formation above.

Disi Formation is overlain by a more than 220 m thick sandstone of the Umm Sahm Formation (Ram Formation) which differs by its weathering having a dark brown surface and by forming vertical fractures and not rounded surfaces. These sandstones, in some less strongly cross-bedded layers contain trace fossils such as the vertical burrows of *Scolithos* and the trilobite traces of the *Cruziana*. Thus they were predominantly deposited in the shallow sea and near the shore. East of the town of Ad Disa, Umm Sahm Formation is exposed along steep massive walls of the sides of the valleies. The cross bedded sandstone holds gravel layers and was deposited by strong currents.

The top of Umm Sahm Formation is usually flat and the following Hiswa Formation may have the shape of a pyramid on top of the flat mountains, well exposed next to

Wadi al Hiswa (Fig. 32). In the Hiswa Formation (also of Jebel al Hiswa to the north of the wadi) is more than about 50 m thick and is composed of fine laminar clay and silt often with red and green color. Its base bears some graptolites which have been determined as *Didymograptus* that indicates early Ordovician (Arenigian) age. These silts, subordinate clay and fine stratified sands are commonly eroded and can be preserved at the base of the following sandstones of Dubeidib Formation. Due to strong compaction, beds appear laminar, but fossil content of especially graptolites present evidence for a deposition in deeper more quiet environment in the open sea.

Dubeidib Formation is represented by a series of laminated, later cross-bedded sandstones of about 85 m in thickness with some more continuous layers with *Scolithos*, more commonly with local occurrences of this trace fossil. Large channels filled with well cross bedded sand characterize the Formation that holds single units which can be followed along the slopes for a long distance along the wide sandy valley of the Sahl Umm Tarifa. The channels are laterally repaced by sandstone with large cross-ripple structure. The depositional environment lay in an area of shallow water with strong currrent and little bottom life, with the exception of dense colonies of worm like animals producing the *Scolithos* and feeding on abundant phytoplancton. The sea can here had been shallow and brackish.

Fig. 32: Cross bedded Ordovician sandstone of the upper sequence of Dubeidib Formation with Sahl Umm Tarifa in continuation of Wadi al Hiswa and with Tarifa Formation above.

Above it lies Tarifa Formation (also Mudawwara Formation or Tubeiliyat Formation) that is around 140 m thick silt sand sequence ending in a dolomitic fine bedded layer (Fig. 33). The sandstones contain rarely shells of *Conularia*. Tarifa Formation is exposed along the road in Sahl Umm Tarifa valley and is characterized by a very rich trace fossil fauna well preserved on many of the bedding surfaces of sandstones (Fig. 34). This formation is quite fossiliferous, both with many layers of trace fossils and some with body fossils. Several of the silt and clay-rich beds contain small phosphatic concretions each of which usually hold a brachiopod with round shape, a conical convex and the other weakly concave shell of apatitic material. The deposition was in continuous change from coarse sand to fine sand and some intercalations of silty clay. The base of the sand beds often preserve trace fossils, ripple marks, often also intraclasts. These document that the consolidated surfaces and layers were eroded by currents and redeposited nearby.

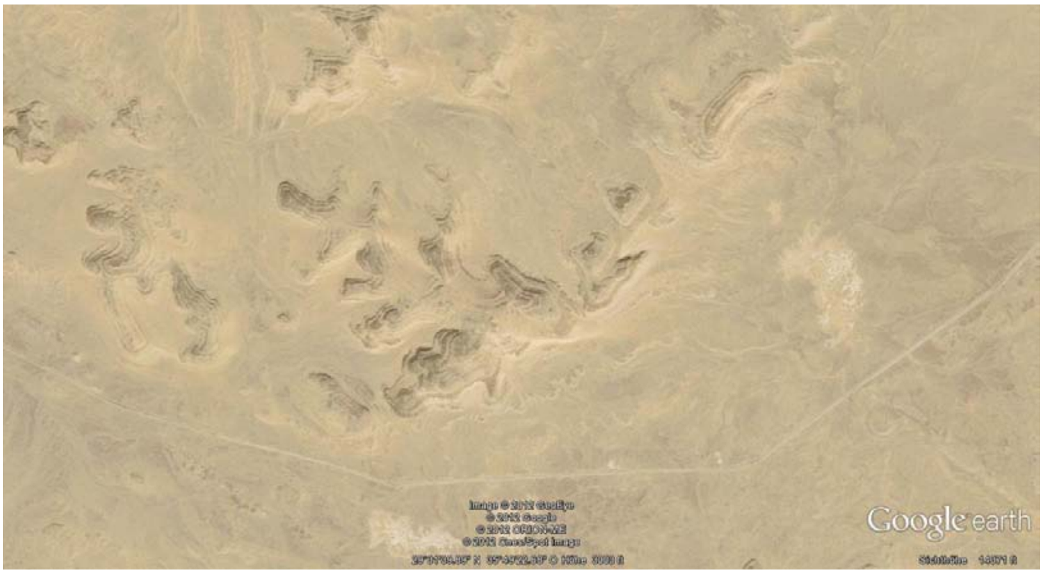

Fig. 33: Outcrop of Ordovician marine sandstones of Tarifa Formation near the road from Wadi Batn al Ghul to Wadi al Hiswa in Sahl Umm Tarifa with many beds containing well preserved fossils and a fine dolomitic sand on the top. A dyke of Neogene volcanic rock forms the row of dark dots below the road,

Fig. 34: Trilobite trail (*Cruziana*) in Ordovician Sandstone (Tarifa Formation) that is also pierced by vertical burrows (Scolithos) of the Conularia bearing section along the road in Sahl Umm Tarifa (Tarifa Formation). (Foto by Marwan Raggad)

Tarifa Formation holds also layers with a large bivalve of the shape of a modern *Mytilus*, and more rarely also of a modern *Pteria* occur commonly (Fig. 35). Small bivalves have left on some layers resting tracks connected to a short crawling trail and formed dense settlements on the sediment surface.

Round brachiopods with one almost flat and another cap-like valves still of the *Schizocrania* (= *Orbiculothyris*) type may be present as well, but still better preserved, it is present in several shale layers intercalated with the sandstone of the upper Tarifa Formation in small round concretions. The shell is nearly round in outline and may reach a diameter of 32 mm. It resembles that of modern *Crania* in shape resembling *Novocrania* as occurs in the reef at Aqaba but is much larger, and it has a shell of Calcium- Phosphate material. One of the valves has a slit through which the pedicle extended to the outside and attached the animal within the sediment or to some hard substrate. The brachiopods were suspension feeders living from organisms of the plankton which they filtered from the water by their lophophores. These are a pair of ciliated and usually spirally arranged tentacles held in the shelter of the shell which takes hold of food particles and transport them along ciliated grooves to the mouth. The brachiopod *Schizocrania* of the Trematidae from the Ordovician belongs to an ancient group of brachiopods with calcium-phosphatic shell consisting of two valves which differ from each other and have at their interior side muscle scars which allow the reconstruction of the movements of the two valves. *Schizocrania* was attached to the substrate through a slit in the pedicle valve. From here the pedicle left the shell, perhaps anchoring the brachiopod in the sandy bottom or to some hard object. Some of the individuals preserved in the concretions have the shells of younger individuals attached to their margin.

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Fig. 35: Ordovician Mudawwara Formation, sandstone with ripple surface and bivalves of the general character of modern *Mytilus*.

Along with the large bivalves of *Mytilus*-like shape and the phosphatic brachiopod more rarely conulariids are present, representing large conical shells of originally phosphatic composition. *Conularia* and relatives has been reconstructed to represent an extinct group of Paleozoic Coelenterata which lived from Cambrian to Triassic. They represent polyps which lived from catching small animals with their tentacles, which probably had nettling devices with which prey was paralyzed, such as is present in modern Scyphozoa. It is thought that *Conularia* was similar in organization to the polyp stage of Scyphozoa, but actually it represented the main stage while in modern Scyphozoa the sexually mature stage is the medusa stage. The conulariid animal had a phosphatic (apatite) skeleton of the shape of a steep, four-sided pyramid with pointed apex. Ornamentation of the skeleton consisted of transverse ribs, and a straight ridge in the middle of each of the flat sides.

The sandstones of Dubaydib and Tarifa Formations commonly have current marks which usually indicate transport of the sand towards NE. Trace fossils such as *Cruziana* tracks produced by trilobites, or *Scolithos* as vertical burrow are present indicating marine conditions. Deposits of sand formed in shallow marine environment or near it, are difficult to date when the fossils in it consist of trails or burrows. *Scolithos* or *Sabellarifex* (pipe rock) consist of vertical tube-like burrows resembling *Scolithos* in the early Cambrian of Wadi Abu Barqa sequence for example and also those of Mid-Jurassic sandstone near Deir Alla. Such vertical burrow structures might have been produced by a variety of animals which live close to each other in the sand and exploit the food available in the water above. Not only worm-like organisms may form similar burrows, but on the tidal flats of the North Sea also the crab *Corophium* produces such burrows in sand, with many individuals close to each other. Also *Cruziana,* which is usually interpreted to have been produced by trilobites, which shallowly plow their way along sediment surface, can be produced as well by a crab by the same behavior, such as a member of the Isopoda when it moves in the same way in search for food. Here in the Ordovician sandstones, trilobites were the originators of these trails, remains of their carapax can rarely be found. Different sizes and composition of their crawling and resting tracks document, that a number of different species of trilobites were present, even though only few skeletal remains have been described from Tarifa Formation so far.

The top of the Tarifa Formation appears to be represented by a laminar dolomite and the following succession is not quite clear due to missing outcrops. This seemingly succeeding section has also been termed Ammar Formation and is exposed in a few exhumed peaks which usually have formed around channel sand that had been deposited in muddy silt (Fig. 36). The large channels may have a base with a conglomerate holding among others pebbles of sandstone composition also well rounded quartz pebbles. The reconstruction of two sand filled channels exposed at Jebel Ammar as glacial deposits of Ordovician age in the SE of Jordan is not convincing. The channels were probably eroded into Cretaceous mud flats, rapidly filled with sand and which subsequently sank into its base forming loading structures on the soft base while the fine water bearing mud below was pushed up and entered the channels sand-forming diaper like structures.

Fig.36: Outcrop of the upper Ordovician top of Tarifa Formation with cross bedded laminar dolomitic sand and the outliers with canal sands of Jebel Ammar in the background and more Cretaceous sandstones even behind that in the east.

A shale bed forms the top of the Ordovician and the base of the Silurian (Batra Formation or upper Mudawwara Formation) and can be dated due to the occurrence of gaptolites. These graptolites represent the remains of pelagic and planktonic organisms consisting of colonies of many interconnected animals. Graptolites became common with begin of the Ordovician when they developed from benthic ancestors with bush-like colonies which were taking up a life floating freely in the sea as Dendroidea. These, still resemble their benthic ancestors. But they evolved into a characteristic group with quite rapid appearance of recognizable species swimming the Oceans until Early Devonian. Their benthic relatives may have continued to exist and are represented by the Pterobranchia with genera such as *Cephalodiscus* and *Rhabdopleura*, which have a tube-like organic skeleton, that is constructed, quite like that of the fossil graptolites. Graptolites began their life with a larva with characteristic cone-like organic tube shell. It later budded to form first one and many more individuals which differ in shape from the larva (virgula). Thus a colony formed with single individuals connected to each other and interacting with each other. The fully grown colony consists of many individuals and grew to a definite size and shape. This member of the Plankton (Zooplankton) fed on smaller Plankton, probably algal cells (Phytoplankton). In general, graptolites during the Ordovician evolved from branched colonies (for example *Dictyonema*) to simpler shape (for example with two branches with the single animal in a row on the inner side of the branches in *Didymograptus* from the base of Hiswa Formation) and during the Silurian with the individuals in one line arranged on a straight or spiral axis (*Monograptus*). Food was collected with ciliated arms. Graptolites existed from early Ordovicium (Arenigium) and became extinct with the Lochkovium in early Devonian. New species evolved quite rapidly, so that every million years of their existence had one or two guiding species. It was assumed that the colonies did not just passively drift in the sea but also rotated by coordinated movement of the tentacles of the many individuals of the colony and thus fished algal cells more effectively.

The Silurian began with or within the bituminous shale of about 18 m in thickness encountered in the subsurface near Batn El Ghoul. This Batra Formation is overlain by sandstone called Ratiya Formation which is present to the east of the road to Mudawara but not well exposed within Jordan, but better in neighboring Saudi Arabia. From Batra Formation chitinozoans and acritarchs have been extracted and provide along with graptolites stratigraphic evidence. It has been assumed that within the shale sequence the upper Hirnantian (latest Ordovician) age is documented, but it may actually represent the early Silurian. This “hot shale” ends in a layer in which organic material was oxygenated. Batra Formation consists of hot shale (radioactive rock) due to its relatively high concentration of uranium. Just before or at about the time of its deposition was the end of the Ordovician ice age and mass extinction occurred during which about 85% of marine species have interpreted to have died. Two pulses of extinction were noted, one at the beginning of the glaciation when sea level was lowered and the second when the glaciation ended suddenly, and sea level rose. In some layers of the hot shale in Jordan, graptolite preservation is three-dimensional with internal moulds of pyrite. This was interpreted to indicate formation in an environment with more oxygen than above and below where all other graptolites are preserved as flat casts. During brief periods of oxygenation also indicated by addition of some fine sand to the mud forming the shale the iron was available in the sediment and pyrite could fill the single thecae of the graptolite colony (rhabdosome) before compaction. The upper part of the bituminous shale belongs to the Rhuddanian deposited during early Silurian Landovery 443-439 Million years ago including the *Akidograptus ascensus* - *Parakidograptus acuminatus* biozone of Jordan (a central nema with a row of individuals on each side). The regionally widespread nature of black graptolitic shale facies in early Silurian suggests that the sea was less well oxygenated than was usually the case at other times. Near Batn al Ghul graptolites belonging to *Monograptus* indicate Silurian age, and even early Devonian was recognized with a marine fauna, but only near the boundary to Saudi Arabia. This predominantly sandy facies continues in Saudi Arabia also reaching a greater thickness here, and it was also traced in the subsurface of Jafr Basin.

Near the Dead Sea Cambrian sandstones are covered by Permian sands and soils. Near the mouth of the Mujib it is overlain by the Cretaceous Kurnub sandstone, and near Petra and south east of it up to 250 m of white Ordovician sandstones of Disi Formation overlie the Cambrian. These are covered by very similar sandstone of Cretaceous age (Kurnub Formation). Ordovician sandstones older than those of the Disi Formation are developed further to the SE in the area north and east of Disi.

No sediments are exposed in Jordan that were deposited between early Devonian and late Permian. Either there was no deposition or former deposits were eroded. During mid-Carboniferous the southern African continent entered an ice age that lasted from 320 to about 270 million years ago. South Africa was for about 50 million years under an ice cap as is the present situation on the continent of Antarctica, but here it is only since about 25 million years. The Permo-Carboniferous ice sheet on the Palaeo -

Gondwana continent increased in mass periodically and withdrew again. Its deposits can be recognized on the different geographical places which nowadays are far from each other and represent parts of the ancient Gondwana continent, now India, Antarctica, Africa-Arabia and South America. The Carboniferous - Permian ice age did not expand as far as Jordan, and here neither the Ordovician ice age nor that during Carboniferous – Permian has left undisputed recognized imprints.

A large change of the biosphere occurred with the appearance of land plants, which by Devonian time covered large parts of the land and in Carboniferous became so common that coals could form, and the soil became affected by the roots of plants. In tropical areas of that time, now encountered in parts of Central and Western Euope and the Eastern USA, large tropical forrests on swampy ground formed coal. Carboniferous rocks are not known from outcrops in Jordan, but were found in the subsurface in northern Jordan in the Azraq Trough where the crystalline basement lies at a depth of 2550 m. A Carboniferous sequence is known from exposures in west central Sinai of the Um Bogma area south of the El Tih Escarpment. Here up to 200 m Carboniferous beds directly overlie the Cambrian sandstones and are overlain by Permian deposits. The Carboniferous sandstone alternates with silty shales and claystones with up to 0.8 m thick coal seems. Plant remains are abundant and have also been recognized from the northern Wadi Qena in eastern Egypt. Here Cambrian sandstone is overlain by a sandstone bearing characteristic plants of the Carboniferous forrest. Among them are the trees *Lepidodendron* and *Sigillaria* of Lycopodiacea as well as bush-like representative of *Calamites* of the horsetails (Equisetacea) and the gymnosperms *Lebachia* and *Walchia* which could be the ancestors of modern pine trees such as *Abies* or *Pinus*. *Sigillaria* has seal-like impressions of their persistent leaf scar marks while *Lepdodendron* has rhombic marks on the bark of the stem in the place of former leaf attachment. Both represent tree-like spore plants of the Lycopodiinae, which nowadays are represented by the clubmosses (Lycopodiales) with small evergreen plants. *Lycopodium* resembles the foliage of *Lepidodendron*, while *Sigillaria* had leaves as present in *Isoetes* of the quilworts growing in wet surrounding of our time. *Calamites* closely resemble modern *Equisetum* which is much smaller and with no wooden stems. *Calamites* stems resemble somewhat the modern bamboo in size and shape, but these two plants are not related to each other.

The margins of the Arabian-African craton constituted a shelf environment with significant uplift during Famennian (late Devonian) to early Tournaisian (early Carboniferous) times. Erosion removed most Devonian, Silurian and Ordovician sediments from the area of Jordan, Palestine and Israel including Sinai. The area was uplifted again at the end of Carboniferous or early Permian and much of the former sediments were removed by erosion. Sandstones with some limestone intercalations of Late Carboniferous to Early Permian age have been recognized in the Negev. In Sinai a limestone containing among other fossils also corals forms the top of the section at Um Bogma. In the southeastern area of Jordan erosion reached Early Devonian sediments. In the subsurface of NE Jordan Carboniferous rocks were recognized. In the southern area in Jordan and Israel and north Sinai erosion reached the Precambrian basement. Altogether over 2000 m of rocks were removed, pointing to a minimal magnitude of this uplift, which is roughly coeval with the Hercynian (Variscan) event elsewhere. During that time the Rhaeic Ocean also called Prototethys was subducted and remnants of it may still be included in an Ocean called Palaeotethys which was part or was transformed into the Tethys. But reconstruction of ancient oceans represent a great problem, since most of the oceanic crust that is older than 250 Million years was subducted below continental crust and is thus no longer available for study and interpretation. Paleogeographic reconstructions are thus often discussed controversially. A complex pattern of vertical motions with a structural high extending from Jordan to the Israeli coast has been noted including the mid-Palaeozoic erosion phase with fission track dating.

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3. Permian and Triassic of Jordan

Permian:

After Jordan had been land for a long time, the area received some continental deposits brought here by rivers from the south and east. Permian-Triassic exposures are found at the eastern rim of Jordan-Dead Sea rift in the steep valleys and the slope above the NE shore of the Dead Sea. Warm and humid climate resulted in the formation of soil. In it iron-oxide pisolites grew aided by the activity of photosynthetic bacteria. Similar pisolites with concentric structure composed of layers of iron-hydroxide grow nowadays in red soils in the South African Natal, for example. Plants growing on the Permian soil consisted of gymnosperms with some characteristic ones with fern-like bipinnate leafs such as *Dicroidium*. This seed fern has relatives in the Triassic of southern Gondwana, now India, South Africa, South America, and Australia.

The Permian of Jordan is represented in the Um Irna Formation that has been named according to the mountain range separating Wadi Zerqa Ma'in from Wadi Himara. Both gorges are located in the northern slope to the Dead Sea. The type section is situated in Wadi Himara, about 3 km north of Zerqa Ma'in hot springs (Fig. 37). Its base is formed by hard Cambrian sandstone of Um Ishrin Formation. Um Irna Formation is about 85 m in thickness and is divided into six well-defined members with fining upward sediment composition. They consist of coarse grained conglomeratic sandstone at the base to medium and fine grained sandstone further up. This sandstone passes gradually upwards into reddish to gray silt stone with surfaces rippled. A dark gray to green clay-stone forms the top. Here single plant fossils as well as coals are included. The two first members have their bases formed by a conglomerate; the finer sands have cross bedding, ripple marks, and occasionally bioturbation. The upper four members begin with coarse-grained, cross-bedded sandstone grading up to thinly lamination (10-15 cm), light gray–gray siltstone and brownish–greenish silty mudstone. Here the upper-most bed of each member is composed of non–laminated clay, which contains iron oxide pisolites of up to 20 mm in diameter (Fig. 38). They are usually

Fig. 37: Cambrian Sandstone overlain by the Permian Um Irna Formation, and the Triassic above with lighter sandstones in Wadi Himara.

autochthonous and have formed in the soil (Fig. 39). Sometimes they were eroded and washed together. Um Irna Formation has also been detected in wells in the north and northwest of Jordan.

Fig. 38: Pisolites concentrated on sandstone surface, reworked soil from Nimra Ma'in.


Fig. 39: Soil section of the Permian Um Irna Formation

A distinct flora consisting of different leaves was found near Wadi Mujib and charcolified wood presents evidence for common wildfires. The depositional environment of the Um Irna Formation was that of a sandy meandering drainage system of a river with poorly aerated swamps and ponds in which plant debris was concentrated. These swampy fan sediments are overlain by such of a dry fan and with fossil soils crossed by some episodic channels in which the pisolites that had grown in the soil were sometimes concentrated. Um Irna Formation is overlain by the Early Triassic Ma'in Formation with indistinct surface of erosion.

During the deposition of Um Irna Formation under aquatic conditions near the transition from Permian to Triassic charcoal formed by wildfires. The Permian sediments encountered in the Negev at about the same time were deposited in a shallow marine environment with the coast nearby. Pollen of gymnosperms and spores of ferns provide evidence of a strong change in the flora that occurred in the transition from the late Permian to the early Triassic. It was discovered that most species living in late Permian did no longer exist in early Triassic and the number of species declined to grow again during the Triassic (Fig. 40a,b). The coaly beds include sporinite which holds pollen and spores in two major morphologies, single lens - shaped grains and bisaccate grains. Outer walls of single lens - shaped grains may display ornamentation such as short, wide spines and bisaccate forms displaying ornamented air sacks. Also fungal spores have a peak at the boundary.

Pollen and spores present evidence of a strong change from late Permian to early Triassic. It was discovered that most species living in late Permian did no longer exist in the early Triassic and the number of species declined to grow again during the Triassic. Very little of that change is seen in the outcrop in the mountainous slope next to Wadi Zarqa Ma’in above the Dead Sea where this boundary is well exposed.

Permo -Triassic biotic crisis represents one of the large mass extinctions in Earth history. This worldwide event can be noted in the change of pollen and spores within the rocks. But the presence of *Dicroidium* in the Permian of Jordan is puzzling, since these trees had their further history in the southern regions of Gondwana. It has been assumed that it is related to *Glossopteris* which lived in southern Gondwana and represents a group of gymnosperms with unclear relation. Its wood resembles that of *Araucaria* living in South America. *Diroidium* and *Glossopteris* are up to 6 m high trees of Permian and Triassic ages and became extinct during Jurassic, somewhat intermediate between Cycadea and Coniferes.

Fig. 40a,b: Plant bearing locality of Um Irna Formation with the fossil transport team. (at the right Abdalla Abu Hamad).

Deposition of Um Irna Formation coincides with the time of supercontinent Pangea that is the result of the subduction of an Ocean called the Palaeotethys or Rhaeic Ocean during the Variscan orogeny. This fused the continents Laurussia and Palaeo-Gondwana, while the area now in Jordan was not affected and lay on a stable (passive) margin of the Palaeo-Tethys Ocean. It is thought that Gondwana rotated counter-clockwise and drifted some 10° north-westward, so that NE Africa and the Arabian platform laid between latitude 10-50°, between 315 and 250 Million years ago (Carboniferous-Permian). Jordan laid at about 20° south. During late Permian rifting commenced subparallel with the northern margin of Gondwana, initiating the Mesozoic break-up of the super-continent Pangea, in which Gondwana was its southern portion. The formation of the passive margin of the Tethys Ocean and the initial development of Gondwana rifts along the present day East African margin are the first tectonic events that indicate disintegration of Pangaea super-continent.

Jordan represented the continental shelf brought about by transgressions coming from the Tethys Ocean since Late Permian time. The sequence of sediments of the

Permian-Triassic is exposed predominantly to the east of the Dead Sea. Permian-Triassic in Israel is close to that found in Jordan. Here subsurface data document that Precambrian is covered by a basal unit of early Permian to early Anisian age. Its basal Sa'ad Formation is about 80 m thick consisting predominantly of sandstone with some coaly shale with plant remains and a few layers of limestone and dolostone. The following Arqov Formation consists of 194 m thick alternating sand, shale and carbonate units interpreted to represent near shore, marine deposits. Fusulinid limestone was encountered in the subsurface of the coastal plain in Israel. It is not certain whether late Permian hiatus in areas adjacent to Jordan results from non-deposition or from post-Permian erosion.

Fusulina is the characteristic representative of a group of large cigar-shaped foraminifera characteristic to late Paleozoic warm water environment. Even though these foraminifera became extinct before begin of the Mesozoic, they are interpreted, like many other large foraminifera, to have lived together with algae in symbiosis. Fusulinidae are similar but not related with the similarly shaped Alveolinidae of Cenomanian in t late Cretaceous. Species of the Fusulinidae are very good biostratigraphic indicators.

Triassic of Jordan

The name Trias is derived from the three lithological units that characterize this period in the European German Basin, the lower red sandstone (Buntsandstein), the central limestone (Muschelkalk) and the upper series with sands, clays and saline deposits (Keuper). Jordan has a similar sequence in its Triassic deposits with the upper part even more characterized by sediments produced in saline environment as in the Keuper (Fig. 41). But the depositional environment of the Triassic in Jordan was in an interior sea on the southern part of the supercontinent Pangea. It represents an extension of the expanding Tethys Ocean onto the southern shelf of Pangea which was to turn into the new Gondwana. The German Basin in contrast formed on northern Pangea on what was to become continent Laurasia. Triassic in Jordan also consists of three parts, a lower colorful sandy unit (Um Irna, Dardur and Ain Musa Formations), a central unit with many limestones (Hisban and Mukheiris Formation) and an upper unit commonly deposited under saline conditions (Iraq al Amir, Um Tina and Abu Ruweis Formations).

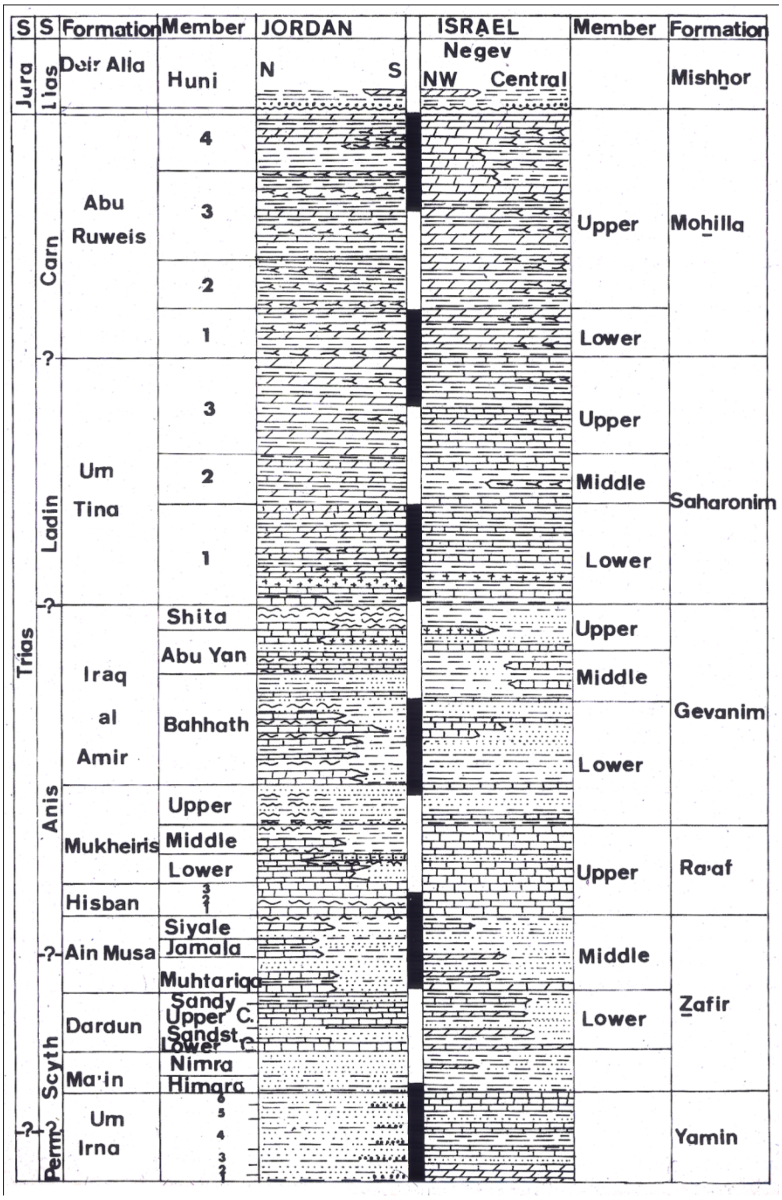

Fig. 41: Triassic sequence in Jordan compared to that of Israel (Bandel & Khoury, 1981)

Exposures of Triassic rocks in Jordan lie in the deep valleys that cut into the eastern slope of the Dead Sea and the southern Jordan valley, their position is from south of Zerqa Ma’in to Naur and again in the lower position of Wadi Zarqa (Fig 42). The total thickness of the Triassic exposed in Jordan is around 660 m, but subsurface data included thickness of up to about 1000 m. Biostratigraphy can be carried out by pollen and spores mainly of gymnosperms on the side of plant remains and pelagic microfossils of conodonts and sclerites of Holothuroidea and the marine ammonites on the side of animal remains. The resemblance of the middle limestone (Hisban Formation) with the Muschelkalk of the German Basin has been recognized very early.

In Jordan the Scythian Ma’in Formation overlies with indistinct angle the Permian Um Irna Formation and measures 35 to 45 m in thickness. Its base is marked by an erosional surface that is only locally with some relief. Ma’in Formation consists of two members (Himara and Nimra), both well exposed in the neighboring Wadi

Mukheiris, Wadi Himara and Wadi Nimra on the eastern slope of the northern Dead Sea. Dark purplish colors characterize Himara Member that consists of beds of thinly bedded sandstone, siltstone and marls of about 26 m in thickness. Burrows of mud living animals penetrated the sediment and their traces are also present on bedding planes. Of the former living and feeding animals burrows of the *Rhizocorallium* type are recognized, the latter are represented by bivalve resting and crowning traces. Former sediment surfaces also bear ripples and in some layers mud cracks which present evidence of exposure of the surface to the air from time to time. Some surfaces have abundant bivalve shells, other layers are covered with the valves of phyllopods like *Estheria*.

Fig. 42: Lower Triassic sequence with Cambrian sandstones at the base, overlain by the purple, Permian Ma'in Formation above, covered with a relict of the former Pleistocene delta of Wadi Zerqa Ma'in into Lisan Lake

Estheria-like crabs (Crustacea, Conchostraca, Branchiopoda) can still be encountered as living animals in puddles and pools which form during the rainy period in the eastern desert of Jordan. In case such a pool exists for a few weeks, eggs that were resting in and on the ground develop into crabs provided with a skeleton resembling that of a bivalve. That carapace is not composed of carbonate but organic chitin, and in contrast to that of most Crustacea it is articulated along a hinge on the back. As among the Ostracoda, both sides of the carapace can be pulled together and the appendages are thus protected below the valve-like sides. In contrast to that of the ostracods the skeleton of *Estheria* is much larger and less strongly mineralized. A similar environment of fresh water or brackish water ponds in dry surrounding was developed at early Triassic time in Jordan. Its deposits are found in the canyons along the northern shore of the Dead Sea, for example Wadi Dardur. These characteristic parts of the crab skeleton which can easily be mistaken for bivalves are common on some bedding surfaces, giving evidence of a similar environment as that periodically developed in lakes and puddles in the desert of Jordan today. Relatives of *Estheria* have lived in that kind of environment since Carboniferous.

This dry land was close to the sea. When the desert planes were flooded it covered its deposits with clay and siltstone which have on its surfaces commonly the valves of Bivalves. Here often both valves are connected, but more commonly they became separated from each other. These mollusks of the shallow sea lived shallowly buried in the sediment with their shells predominantly composed of aragonitic calcium-carbonate. Both valves are attached to each other by the organic ligament. This structure serves as elastic opening device pressing the valves to open, and the bivalve has to use muscular force to close its shell. When the bivalve is dead, the ligamen pushes the valves to open. The ligament may later be decomposed by the activity of bacteria usually not long after the bivalve dies. In that case valves are no longer connected to each other, separating when washed by currents. Thus bivalves with both shells still together indicate preservation at the place on which they lived (autochthonous) or of deposition very close to it when the ligament was still intact. Bivalves from early Triassic belong to the heterodont groups and are usually not well preserved, since their aragonitic shell has become dissolved before the sediment was compacted and have thus been flattened and deformed.

Rhizocorallium represents a very characteristic type of burrow in the sediment preserved as trace fossil. The burrowing animal excavates a U-tube in the sediment which is enlarged by taking away material from the outer side of the tube and re-deposit onto the inner side. Thus a U with curving filling sheets on its inner part is formed. The same type of burrow has been constructed by different types of animals since Cambrian time. For example the crustacean *Corophium* which represents a member of the Amphipoda still constructs such a home living in the tidal flats of the North Sea. From *Rhizocorallium* and the very similar *Diplocraterium* it can thus be reconstructed how the burrow was built and what it was used for. In Jordan very well preserved *Rhizocorallium* are also known from the some limestones in the mid-Jurassic and from the marine beds in the upper Kurnub (Fig.43).

The upper member of Ma'in Formation (Nimra) is about 21 m thick and begins with sandstone and siltstone beds commonly with fine to coarse flaser structure (Fig. 44). They are reddish and greenish in their clay-rich portions and carbonate-rich beds are present, some of which show beach rock structure and holds clasts. The upper member consists of fine white sandstone arranged in cross-bedded units of 50 to 150 cm in thickness. Bioturbation may or may not destruct original bedding structures. Some pure limestone units are included in the upper portion of the member and may have clasts that represent parts of former burrows, as is characteristic for many beds in Hisban limestone.

Fig. 43: End part of Rhizocorallium burrows eroded and exposed on the surface of the bed of the Dardur Triassic

Fig. 44: The replica of a bedding surface of Zerqa Ma'in Formation with cyanobacterial wrinkles crust in former puddles and smooth former dry surfaces and bivalve shells

Beach-rock forms within the sands of the shore and clasts form when puddles with a muddy bottom dry out and mud cracks appear. The hard sherds thus formed can be picked up by the current and transported to a new position to be deposited in fine grained sediment and thus form the clasts as were noted in some layers. Beach rock is produced by cementation of sand due to mixing of pore water of different salinities and to the drying out of this sand. This way carbonate cement grows between grains fusing them and the sand is transformed into rock. The hard bed thus formed in the beach environment can be eroded out, broken into pieces and can also be the source to the clasts as are present in some layers. Flaser is small ripples that may have cross bedding with different directions next to each other and with the small sand dunes coated with silt and clay. They form within intertidal environment with flood time followed by slack time succeeded by ebb time. This causes the water and the sand to move in two directions. Between these movements, periods of quiet water developed during which finer suspension settled on the rippled sand surface.

The following Dardur Formation of about 60 m in thickness at its type locality was also deposited mostly within the tidal zone or in very shallow water. But fully marine influence of the open sea is documented also by the occurrence of organisms such as crinoids which need water of normal salinity. Also limestones are more dominant in the North of Jordan as is evident from the subsurface near Suweilih to the north of Amman. Dardur Formation crops out at the northeastern margin of the Dead Sea and in the deep valleys between Wadi Mukheiris to the north and Wadi Abu Khusheiba to the south. The top of Dardur Formation lies near the hot springs of Wadi Zerka Ma'in. Its age is from Scythian to early Anisian as is documented by conodonts and palynomorphs (organic microfossils, including pollen and spores). Its lower carbonate member, about 11 m in thickness includes some thinly bedded silty shales and fine grained sandstone and dolomite. These layers show some bioturbation, but only few benthic animals settled to the bottom substrate so that original lamination was not destroyed. It is succeeded by 15 m of thick, brownish cross–bedded sandstone topped by carbonate cemented sandstone and dolomite and marl with fine lamination.

Fig. 45: Zerqa Ma'in Formation base of bed with Stromatolitic wrinkles and bivalve shells.

Intra-formational conglomerate of limestone and shale pebbles occur here documenting intratidal environment. The upper carbonate member of Dardur Formation is about 23 m thick and consists of similar deposits as in the lower carbonate member. An upper sandy member with 12 to 20 m in thickness follows and consists of sandstones with load casts, bioturbation and ripple marks. Sand–filled mud cracks, scattered bioturbation, canal-fills with quartz pebbles at canal bases, in addition to some stromatolitic beds and other composed of crinoidal skeletal remains are present (Fig. 45). These characters of the sediment give evidence for a deposition of Dardur Formation near the coast, on intertidal mud flats environment in the basal member, near the shore in the middle one, and due to the presence of crinoid remains in the shallow sea in the upper layers. The quartz pebbles in channels are partly rounded and partly angular and have probably been washed from the Precambrian basement which cannot have been far away. Thus the shore during Dardur deposition was probably in the south and east of Jordan and areas from which the pebbles were washed off were not covered by Paleozoic sandstones.

Crinoids (Crinozoa, Echinodermata) are common in the Triassic sea. Sometimes their skeletal elements compose characteristic beds. Single elements of their skeleton have the same composition and basic structure as their relatives had in the Cambrian. The construction of their body and the mode in which they lived are known much better since the Triassic representatives are close to still living species. Most elements represent parts of the stem or stalk which is either rooted in the sediment anchored by branches (cirri) or has its base cemented on hard substrates. These disc shaped ossicles here usually have the shape of low cylinders traversed by a central canal. They have been altered during early diagenesis into single crystals of calcite.

Crinoidal limestone thus sometimes resembles a marble with its large crystals. At the end of the stem the crown (theca) is found that has most of the intestines and is connected to the arms. The composition of the globular theca as well of the arms is also of many single skeletal elements which separate from each other when the animal is dead. During activity the arms are spread out to screen the water for food, which is taken hold of by fine organic ambulacra. Crinoids with similar organization of their crown are still to be found in the coral reefs at Aqaba, but they differ by not having a long stalk. Here they spread out their richly branched crown and screen the water for prey, as did their relatives in the Triassic sea.

Ain Musa Formation is well exposed in Wadi Ain Musa and has three members (Muhtariqa, Jamala and Siyale) each of which have their type section in the localities with the same name (Fig. 46). The base of the formation was in part deposited by rivers, and most of the layers above in the shallow sea. In Wadi Mukheiris Ain Musa Formation is about 100 m thick, about 20 m thicker than further to the south in the type section. Its basal Muhtariqa Member is about 45 m in its type locality at Rujm el Muhtariqa hill, situated at the end of the Wadi Ain Musa and consists of a thick sandstone with large cross beds and some layers of flaser cossbeds. Its deposition in a partly fluviatile environment bordering to intertidal flats can be reconstructed. Also conglomeratic layers with quartz pebbles give evidence of land with erosion nearby. Only several km to the North into the sandstones also limestone, marl, siltstone, dolomitic limestone are intercalated. Thus shore environment had been replaced by shallow sea and intertidal flats. Here clay clasts document redeposited eroded intertidal surfaces and bioturbation the presence of much life in the sediment at times. Locally glauconitic interlayers and a bed of stromatolites occur. Jamala Member is 15-28 m thick and has a type locality below the confluence of Wadi Jamala with Wadi Ain Musa at the spring of Ain el Jamala. It consists of intercalated sandstone and siltstone. The cross-beds commonly have rippled surfaces and channels are present with pebbles of well-rounded quartz at their base, also with tree trunks. Trace fossils represented by crab burrows and C*hondrites* burrow systems are present in the siltstone –marlstone and fine grained sandstone. Besides burrows, ripples, flaser beds, sandstone and siltstone clasts, and sand filled desiccation cracks are present. Siyale Member is about 30 m thick and is composed mainly of the greenish to gray intercalated marly claystone and siltstone. In some layers glauconite and the brachiopod *Lingula* are common. The common occurrence of drift wood, clay balls and quartz pebbles layer in addition to alternation of thin to very thin beds of sandstone, siltstone and marlstone is evidence for near shore environment. Northwards this member is represented by a sequence consisting of sandstone, limestone layers, dolomitic limestone and siltstone, indicating the increased influence of marine conditions during the deposition of the sediments.

Chondrites represents a very characteristic burrow system produced by a worm-like animal that fed on sediment. The animal produced a central tube from which side tubes branch off which in turn may also branch. The animal keeps contact to the surface water along the central tube and fed on sediment around the central tube by using the side channels, backfilling them when returning to the main burrow. Often this plant-like structure has been formed when sediments poor in oxygen are used as source to collect food. Nowadays, in the North Sea flats an annelid worm *Heteromastus* is producing similar feeding burrows by feeding on bacteria from oxygen depleted marine mud.

Fig: 46. Triassic sequence with Ain Musa Formation and Hisban Limestone above (Wadi Dardur)

Lingula is a representative of an ancient group of animals usually placed in the Brachiopoda, with a branch which has phosphatic shell composition. *Lingula* has Cambrian roots, and Ordovician species closely resemble the Triassic ones which on the other side are almost indistinguishable from those still living in tropical estuarine mud where their mode of live can be studied. *Lingula* is known, virtually unchanged, from fossils extending back at least 400 million years ago and can be considered a good example of a living fossil. *Lingula* burries in the sediment with its stalk-like foot (pedicle) and leaves a vertical burrow structure with backfill laminae, when the animal moves up in its burrow when sedimentation occurs. Food consists of planktonic organisms which are sucked into the shelter of its shell through two holes kept open by the mantle (incurrent flow) and water is expelled again through a third hole (excurrent flow). The water is driven by the cilia arranged on the coiled arms (lophophores). Movement of the valves is carried out by a complex assemblage of muscles. Nowadays *Lingula* lives in tropical estuaries as for example found at the Australian east coast. *Lingula* also lives in much smaller estuaries and muddy shore areas in the Red Sea but is not found along the Jordanian shore, only its larvae appear now and then in the Plankton here. Modern *Lingula* is primarily an Indo-Pacific genus and it inhabits vertical burrows in soft sediments with the anterior end upward at the sediment surface with only the two holes formed by the incurrent and exhalent water stream seen on the surface.

When the sediments of Ain Musa Formation were just deposited they consisted of soft sand, silt or mud, in the latter case mostly composed of lime. The environment of deposition was estuarine when *Lingula* is found and fully marine where crinoids lived and their remains are common. In the marine environment glauconite formed within the surface mud as autochthonous clay mineral. When the mud fell dry on tidal flats it cracked and hard mud sherds formed. Especially when cyanobacteria grew in the surface layer and produced mucus these fragments were solid sherd-like and could be transported by returning water without disintegrating. In the sandy beaches of this environment, due to cementation, beach rock was formed. In case the water became saline, either in a lagoon or within the mud as pore water, the calcareous mud changed into dolomitic mud during early diagenesis by addition of magnesium ions to the calcite crystals. An early diagenetic change also transferred the porous skeletal elements of the echinoderms into calcite crystals. Later, all aragonitic calcareous particles either dissolved or were transformed into calcite, and this dissolution provided the calcareous material needed to transfer the muds into solid limestone by calcitic cements forming between particles.

Hisban Formation with 35m thickness in Wadi Dardur and 30m in Wadi Hisban consists predominantly of gray, stylolitic, limestone with wavy bedding that was totally churned by burrowing animals and bears many fossils, such as brachiopods with calcitic and phosphatic shell, oyster-like bivalves and steinkern preservation of *Myophoria*-like bivalves (Fig. 47). It is hard, often nodular and has a spotty appearance. The bulk of the limestone is characterized by calcareous, lithified burrow systems, all of the same undulating type. The base and top of Hisban Formation can be seen in Wadi Mukheiris and Wadi Dardur. Here the base is marked by a sharp contact between the green–gray marlstone–siltstone of Ain Musa Formation and the massive limestone of the basal unit of Hisban Formation, and the top is represented by the sharp transition from the limestone to marl to the cross-bedded sandstone of the base of Mukheiris Formation, as is well exposed in Wadi Mukheiris. Conodonts document Anisian age for Hisban Formation. In Jordan the depositional environments of Hisban limestones was marine, probably not a deep one and not close to the shore in most parts of its sequence. Oolites known from the subsurface near Suweilih give evidence also for the presence of shallow shoal environment. Similarly beds of oyster-like bivalves in Wadi Hisban indicate shallow water with a lot of Plankton (Fig. 48). Intercalated crinoidal limestone beds in Wadi Dardur are a sign for good normal marine conditions.

Fig. 47: Hisban Formation with limestone composed of reworked burrow – tubes from Wadi Hisban

Stylolites formed during late diagenesis when the limestone was fully consolidated. They represent sutures which form perpendicular to pressure onto the rock column and are the result of solution. Stylolite seams often follow fine irregularities in the bedding, often surround fossils and are found especially in very fine grained limestones. The seam is coated with material, mostly clay which was present in the limestone that later on dissolved. Nodular limestone on the other hand is also a diagenetic feature that formed much earlier in the diagenetic history of the Hisban Limestone. When the bioturbated lime-mud with a little clay in it became cemented, deposition of cement started locally. Its production was connected to a depletion of some carbonate nearby, so that centers with more carbonate grew into nodules and the area around them was comparatively enriched in clay. After some period of migration and concentration on the one side and solution on the other pore water stopped migrating but the sediment changed from more or less similar limy mud to nodular limestone.

Usually, burrows that penetrate the sediment are preserved as trace fossils and when the sediment is eroded burrows are usually destroyed. In case that trace fossils are present in several beds of Hisban limestone this is quite different. Here the constructing animals, crabs (Crustacea) or worms (Annelida), kept the burrow open for a long time pumping water through its tubes into their subterranean home. The fresh water from the surface reacted with the pore water within the lime-mud that composed the sediment and tube walls became cemented. In the North Sea flats for example, the sand worm *Arenicola*, may live for a long time in one and the same U-shaped burrow. Here it pumps water into the burrow and expels it together with the feces at its end. The part of the burrow in which water is pumped through sediment remains soft and is used to filter food particles from seawater sucked through it. It thus, is enriched with food eaten by the worm from time to time. The other part of the U tube remains stable and the walls may be enforced by mucus produced by the worm and by deposits of minerals from the pore water coming in contact with sea water. In case of *Arenicola* iron oxides can produce a stable tube that can be washed out and act like a body fossil. In the case of Hisban Formation burrows the wall was mineralized by calcite during the activity of their inhabitants. When currents washed away some of the soft calcareous mud the cemented portions of the burrow structure were exposed and enriched into tube-layers which are characteristic to some beds in Hisban and Mukheiris Formations (Fig. 49).

Fig. 48: Coquina of oyster-like bivalves from Hisban Limestone in Wadi Hisban

The bivalve *Myophoria* has an aragonitic shell with somewhat triangular shape with sharp corners beginning at the umbo. There can be ornament on the posterior area of the shell surface and that distinguishes different species. The hinge has a strong median tooth that may be split (schizodont). *Myophoria* occurs in the Muschelkalk of the German Basin as well as in the Jordanian Triassic, especially Hisban and Mukheiris Formations. Its preservation is in an internal mold or cast of the shell on mud which was cemented before the aragonitic shell with nacreous composition dissolved, leaving a cavity which may have filled with cement carried by the pore water. *Myophoria* belongs to the same group of bivalves with a hinge with heterodont teeth and a shell with an inner layer of nacre as *Trigonia* that is common in the Jurassic of Jordan. Both are members of the Palaeoheterodonta which have survived in the one genus *Neotrigonia* which still lives in the Pacific along the West-coast of Australia.


Fig. 49: Diplocraterion- like burrows in Mukheiris Fromation

The base of the Mukheiris Formation is defined where thick massive limestone beds of Hisban Formation are conformably overlain by sandstone and marly claystone. Conodonts, holothurian sclerites, ammonites (Ceratididae), brachiopods (*Coenothyris*) and bivalves (*Placunopsis*) are present and spores suggest an Anisian age. Mukheiris Formation is about 80 m in thickness in Wadi Mukheiris which represents the last most northern deep canyon ending directly at the shore of the Dead Sea and is also well exposed in the next Wadi, Dardur just south of it. It can also be recognized in wells in north and northeast Jordan. Three members are distinguished of which the lower is 30 m thick and consists of fine-grained, cross-bedded, sandstone with ripple surfaces and intercalations of marly claystone and siltstone. Channel–fillings and driftwood are present and clay beds contain many fragments of gymnosperm leaves still bearing the cuticles. Its upper part is calcareous sandstone with glauconite, much bioturbation and many fossils such as bivalves, ceratitid ammonites and bones of an amphibian. The middle member consisting of clay and silty shale is about 30 thick and contains *Lingula*. The upper member is about 18 m thick and of fine to coarsely grained, cross bedded sandstone and thinly laminated, rippled marlstone and siltstone with many plant remains. Sandstone beds which fill former channels contain a fine conglomerate of quartz pebbles on their base. The member ends with dark to black, thinly laminated, clay-stone truncated by the unconformity of the Kurnub Sandstone of Early Cretaceous.

Fig. 50: Jaw of vertebrate and Ceratites from Mukheiris Formation

The typical ammonites of the Triassic period which had entered the marginal seas belong to the group around the genus *Ceratites* (Fig. 50). It represents an ammonite as we know them since they evolved during early Devonian and became extinct by the end of Mesozoic. The characteristic feature of Ceratitidae among the ammonites is the mode in which the chamber walls are attached to the inner side of their shell. Here those parts of the wall pointing into the direction of the head are well rounded (saddles), while those parts pointing to the early part of the shell (lobes) are split into several finer lobes and saddles. *Ceratites* and related ammonites from the Jordanian Triassic are very similar to those found in the German Basin at about the same time. But when compared in detail they belong to different species, thus documenting that the continental sea in which Hisban and Mukheiris Formations were deposited far away from the German Basin on the other, southern side of the Tethys Ocean. A certain group among the many different types of Ceratitidae that lived in the Tethys obviously liked the shallow warm shelf seas and evolved in them to similar looking but distinct species.

The thin small bivalve interpreted to be close to *Placunopsis* lived attached to the substrate and resembles modern *Anomia* which can be found in the Gulf of Aqaba. But relationship to the Anomiidae among the bivalves is not clear since Triassic species may also be related to ancestral oysters (Ostraeidae). Its preservation is so good since much of its shell is originally composed of lamellar calcite, as is still the case with *Anomia* as well as most oysters. *Placunopsis* settled on hard substrates and it may also be found attached to the shell of *Ceratites*, and in that case it has preserved its original shell while the ammonite is preserved early as filling, because its shell was aragonitic.

Conodonts are phosphatic microfossils of usually less than 1mm in size and resemble teeth often with many cusps, but may also have plate-like shape with rounded or concave base and noded or dented upper side. They represent a part of the skeleton of a pelagic, free swimming organism that has no living representative. The conodont apparatus is interpreted to have been present in the gill region of a fish-like chordate animal resembling the lancet-fish *Branchiostoma* which lives in the loose sand of modern oceans. Conodonts can be etched with acetic acid from pelagic limestones and occurred in Paleozoic up to the end of Triassic. In Jordan they have been extracted from some mid-Triassic limestone beds in the outcrop in the Wadi Shita area near Naur in great numbers, but have also been discovered in older limestones. Conodonts have existed from the Cambrian to the end of Triassic and they are of stratigraphical importance from late Silurian until their disappearance.

Good preservation is present in the brachiopod *Coenothyris* from Wadi Naur. It closely resembles the modern brachiopods of the *Terebratula* type as found for example on the coast of the cooler Pacific of New Zealand or in deeper water attached to stones along the European Atlantic. A very similar brachiopod lived in the Muschelkalk of Germany at about the same age. These filter feeding animals are attached to the substrate by a stalk (pedicle) that extends through a hole of one valve, the larger one (pedicle valve). The hole lies in the umbo with a round perforation. The smaller valve carries the supportive structure of the lophophore represented by a calcareous loop. This loop differs among Terebratulidae and has also changed through times of their existence. For the determination of the species there is need to know its shape, since the outer shell shape of different Terebratulidae is quite similar. Similar terebratulid brachiopods are common in the Jurassic, and few are found in the Late Cretaceous-Cenomanian of the Ajloun area. Their shell is calcitic and therefore, usually well preserved, since both valves are connected by teeth of the loop carrying smaller valve fitting into grooves of the opposite larger valve pedicle. Due to the presence of this hinge the shell is usually preserved with both valves in place. The whole group of these brachiopods are placed in the Articulata which have their valves articulated by projections of one valve into grooves in the other shell holding them together even after death. Movement of the valves is by several pairs of muscles, which leave scars on the inner side of the shell at their place of attachment. Tiny relatives of the genus *Argyrotheca* are still living attached to dead corals in the frame of the reef at Aqaba and still display the major characters of the group.

Holothurians are echinoderms with elongated soft body with mouth and anus situated on opposite ends which rarely are preserved as a whole. Here small sclerites are present within the skin and after death many of these calcitic wheel, needle or anchor-like sclerites remain. These animals can be observed in the shallow reef lagoon at Aqaba and here still function in the same way they had in mid Triassic times. Holothurians move along with ambulacral feet on the base of their body and may also burrow in the sediment and catch or collect particles with the longer ambulacral arms which lie around their mouth. The particles collected that way, enter the very long intestine and become digested. During this process organic material is dissolved and mineral material rubbed against each other and thus corroded and ground. A holothurian thus acts as a biological mill grinding especially calcareous particles down to smaller size. In the shallow Adriatic Sea it has been observed that the particles on the surface enter the digestive system of the holothurians living there about ten times within a single year. Also in Aqaba one can find such sediment-feeding cucumber shaped echinoderm often on the end of it trail of feces. The biological mill grinds down shells and other fragments of calcareous material to finally mud leading to the sediment that later transforms into fine limestone or marl. The sclerites of different species of Holuthruroidea have quite different shapes and evolution was sufficiently rapid that they can be used as biostratigraphical indicators, useful in the Triassic.

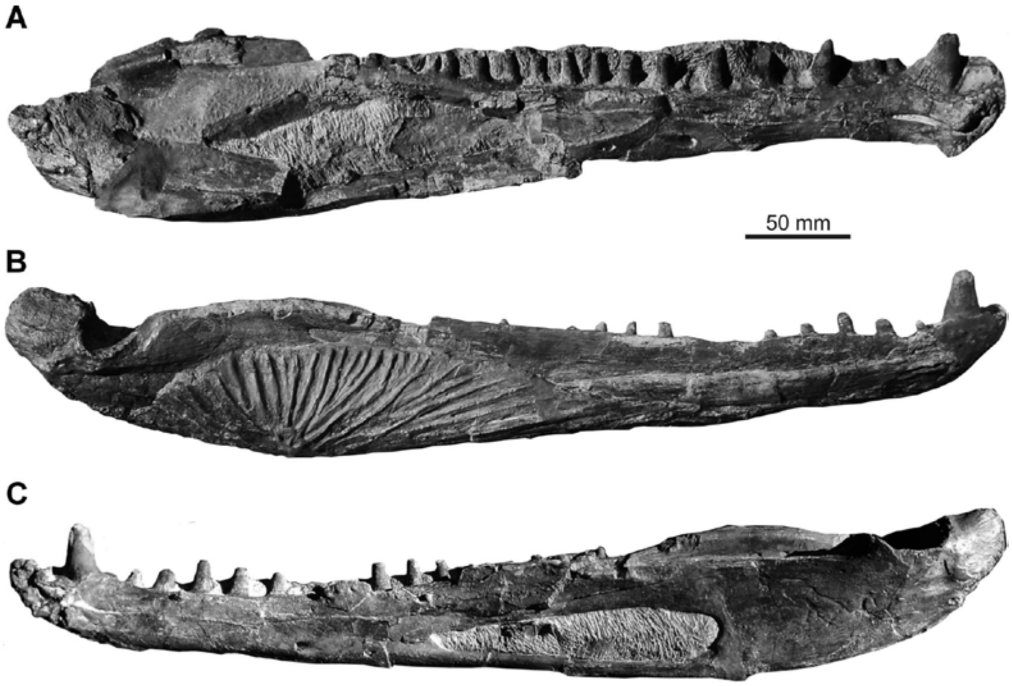

Fig. 51: The jaw prepared by Rainer R. Schoch and published in Schoch (2011 fig.2)

The vertebrate is represented by a 50 cm long scull that belonged to a temnospondyl amphibian of the group of the trematosaurs which were distributed world-wide and lived in shallow marine environment. The Jordanian trematosaur was at least 3 m long and lived in water within shallow marine environment (Fig. 51). The excellent in-situ preservation of teeth indicates that the mandible was not transported over a longer distance. In subtropical climates similar to the preserved situation, skeletons decay at a fast pace, which in turn indicates that the mandible must have been buried rapidly

Just north of Na’ur an about 160 m thick section of Triassic rocks with Iraq al Amir and Um Tina formations are exposed, a part of the sequence that had been eroded further to the south before Kurnub Sandstone was deposited. Iraq al Amir Formation with about 95 m is exposed in Wadi Salit and Wadi Naur with three members. The lower Bahhath Member of Iraq al Amir Formation consists of about 26 m of fossil bearing sandy limestone, lime- cemented sandstone, marl, fine sandstone, siltstone, and marly clay-stone with laminations. The macrofossils reported comprise *Placunopsis*, terebratulid brachiopods, crinoids ossicle and ceratitid ammonites. In the limestone beds crab burrows of the *Ophiomorpha* type form an interconnected system and scratch marks left from construction still present on the walls. Other limestone beds are composed of reworked burrow tube of the type that is characteristic to the Hisban limestone. Depositional environment was shallow sea with open marine conditions. The middle Abu Jan Member consists of predominantly carbonates and is about 40 m thick and in part glauconitic. Some beds bear many fossils, such as fillings of gastropod shells, bivalves, *Ceratites*, terebratulid brachiopods and bones of vertebrates and teeth of sharks. In layers a bone bed is developed consisting of numerous small and large bones which are usually fragmentary and phosphatic concretions. The upper part is dominated by hard limestone and oolitic limestone with crinoids ossicles and some spines of regular seaurchins. Abu Jan Member terminates with about 2 m thick bed of sandy dolomite and limestones with irregular pitted hardground surfaces and intraformatinal limestone conglomerate. It thus appears that after deposition in normal marine environment with abundant marine life a more saline phase occurred changing the calcite into dolomite during early lithification. An amazing feature within the upper Abu Jan Member is the intrusion of up to 5 m thick sill of diabasic magma. This volcanic material was emplaced in late Jurassic or early Cretaceous time (Fig. 52).

Fig. 52: Exposed basaltic sill in Iraq al Amir Formation with Krebs standing on it

The upper member (Shita) is about 25 m thick with fine grained limestone, marly limestone and thinly bedded marly clay-stone, and an upper dolomitic limestone and hard, cellular dolomite. The marl contains feeding structures of the *Zoophycus* type. Hard-ground surfaces within the limestone were encrusted by oyster-like bivalves and pits contain gastropod steinkerns and the spines of sea urchins. A single layer with pyritic dark limestone and shell debris of *Lingula*-like brachiopods contains many conodonts. Wadi Shita which discharges into Wadi Naur has this member exposed with laminated stromatolitic carbonates of grading into the basal Um Tina Formation. In Israel similar beds have been dated as of Ladinian age based on conodonts, an age that was confirmed with the same fossils and with holothurian sclerites also from Jordan.

Um Tina Formation in Wadi Um Tina 1 km south of Wadi Naur exposes about 70 m of the formation, but it may be up to 200 m thick in the subsurface. With the begin of Um Tina Formation the open sea no longer had direct contact with the depositional environment represented by its sediments. All sediments are characterized by laminar bedding usually in wavy stromatolitic structure. Bioturbation is present only in some beds often represented by the network of former crab homes, and is more rarely developed further up in the section. Gray, hard, fossiliferous limestone, micritic limestone and thin lamination of gray marly claystone form the base, and here conodonts indicate a Carnian age. The upper part is dominated by 1–2 m thick beds of gray marly claystone intercalated with yellowish, fractured limestone, and dolomitic limestone. The top is truncated in the valley below Naur by the basal Kurnub sandstone of early Cretaceous age. In the subsurface the top of this formation was defined by an increase of gypsiferous beds as noted from the well log of Suweilih well.

The most interesting stromatolites site of Jordan can be visited in the valley below Naur not far below the truncation of Triassic rocks by Kurnub Sandstone (Fig. 53). Like the Precambrian stromatolite from the crater lake of Abu Barqa Formation to that formed nowadays in the fresh water springs which issue into the extremely salty water of the modern Dead Sea they were and are composed of Cyanobacteria. Here cells commonly are arranged in rows and surrounded by mucus. In case of calcifying cynaobacteria the CO2 needed for photysynthesis is taken from the HCO3 ion present in the water. Due to this process calcium bicarbonate (Ca (HCO3)2 is transferred to calcium-carbonate (CaCO3). Calcium-carbonate is deposited within the mucus cover of the cyanobacteria the structure formed is tubular and resulting fossils have received the names *Girvanella* or *Porostromata*. Is the lime deposited between bacterial crusts the stuctures are called Stromatolite or *Spongiostroma*. In case they are deposited around a core onkoides or ooides form, which are distinct from each other by size. The first is larger and the second of the size of sand grains. Cyanobacteria may form calcareous deposits in the sea, in fresh water, or even on land. Here crusts as caliche forms or they grow in the soil as pisolite using dew or pore water for their life. In a normal marine environment, since the existence of grazing invertebrates, cyanobacterial crusts are usually destroyed by these, only in saline environment they remain intact.

Fig. 53: Stomatolite from Naur

Repeated succession in a shallowing upwards carbonate-sabkha sequence with a tendency toward more marine conditions towards the NW may be observed in Jordan.

Cycles show a gradation from subtidal oolite shoals, into lime mud of a lagoon, intertidal algal mud with some stromatolites, supra-tidal laminated mudstone and intra-clast layers and nodular anhydrite and in some cases rock salt salinal deposits. The upper 500 m of deposition of Triassic sediments in Jordan is dominated by chemical deposits such as carbonate, gypsum and salt, and only suspended clay in water coming from the continent reached the area.

Abu Ruweis Formation, after Wadi Abu Ruweis next to the gypsum exposures in the canyon, is exposed along the lower Zerqa River (Fig. 54). Most of this Formation is preserved in the subsurface of Jordan and only the last deposits are exposed. An about 42 m thick sequence of layered gypsum is exposed in several quarries. Massive gypsum is intercalated by silt, sometime black clay and dolomite. The gypsum unit is overlain by about 13 m of intercalated clay, marl and dolomitic limestone. Plant fossils here are large leaves of the fern *Phlebopteris*. Palynomorphs (pollen and spores) of Abu Ruweis Formation provide Carnian age. The uppermost member of Abu Ruweis Formation has besides ferns also *Lingula*. The formation is terminated and overlain by about 3 m of deposits that consist of colorful clay-stone and pisolitic paleo-soil which formed in the transition time to the Jurassic.

Fig. 54: Gypsum of the upper Abu Ruweis Formation

Also the German Late Triassic holds *Phlebopteris* especially in the Rhaetian sandstone with which the history of the German Basin ended. The Jurassic characters of sea connections occurred first, but it was followed by a withdrawal of the sea from the area (regression). This is very similar in Jordan. *Phlebopteris* is known from the Early Keuper of Europe and was also noted in the Jurassic. *Phlebopteris* is a member of the fern family Matoniacea which is known from Mid Triassic onward into the Jurassic. It is thought that *Weichselia* as was found in the lower Kurnub is one relative of the family. Modern *Matonia* has similar spores and lives in Malaysia. In case of

Phlebopteris they are called *Diclyophyllidites* and are of a triangular shape (trilate) with three branched cleft and fine morphology as have been reported to occur from Ladinian to Bathonian.

Gymnosperm pollen and fern spores have very good preservation potential even though they are very small (0.05-0.07 mm). Modern pine trees such as *Pinus* in Jordan have pollen grains with a central body to which two bladder-like sacs are placed (bisaccate). Bisaccate conifer pollen occurs from the late Paleozoic onward, while leaves or cones of Pinaceae first appear in Mesozoic. Minute differences of ornament on the pollen grains allow distinguishing different ones and these have been named, without knowing to which gymnosperm species they belong. The group of conifers to which modern pine trees represent relation are known since Permian time with *Walchia* and Triassic time with *Voltzia*, for example from the German Basin.

The Jordanian deposits of Triassic rocks with about 1000 m in thickness can be compared with those that have been described from southern Israel. Here the Permian-Triassic succession has been suggested to be about 1500 m thick. The early Triassic 130 m thick sandstone is succeeded by carbonates caped with sandstone (Yamin Formation). About 240 m thick alternation of shale, fossil bearing limestone and sandstone compose the Scythian Zafir Formation. Anisian Ra'af Formation is equivalent to the Hisban limestone in Jordan and Gevanim Formation in part to Mukheiris Formation. Its thickness of about 270 m is calculated from a composite section interpreted to have been deposited in near shore to tidal flat environment. In Israel the change to a predominance of chemical deposits occurred in Ladinian time during deposition of the Saharonim Formation. The uppermost formation of Triassic in Israel is Mohilla Formation that consists of up to 200 m of anhydrite and dolomite with some shale, limestone and marl deposited in an environment of hyper-saline supra-tidal flats during Carnian to Norian age. At the top of the Triassic section in the subsurface of Israel it was noted that the Triassic Jurassic boundary is characterized by an extinction of most Triassic taxa. The end-Triassic mass extinction (about 201 million years ago) has been documented in terrestrial ecosystem turnover and a severe loss in marine biodiversity. The Triassic – Jurassic boundary is the time during which it came to almost the end of the ammonites, great problems for many gastropods, almost disappearance of the newly evolved aragonitic corals and the extinction of the Conodonta. From carbon-isotope data extracted of land plants a strong carbon-13 depletion of the end-Triassic atmosphere was reconstructed that occurred within only about 20.000 years. Vegetation changes reflect strong warming and the end-Triassic events are linked to methane-derived massive carbon release and associated climate change. Among the animals of the sea many gastropod lineages which have survived even the Permian –Triassic faunal crisis now ended.

Deposits from Norian have not been recognized in Jordan. At that time about 220 Million years ago continental sandstones are reported to have been deposited in the Sinai area. During spreading of the oceanic crust of the Tethys a Cimmerian continent departed from Gondwana and has now remnants in the Alps. During late Triassic time much of this terrain was covered by large tropical lagoons, with reefs on their margins to the open Tethys Ocean. This continental crust had detached from Gondwana and migrated to the north, caused by the formation of new oceanic crust between it and Gondwana and by subduction of former oceanic crust to the north of it. In that way it moved from one side of the Tethys to the other side, and from one continental shelf that is the same as that from Jordan, to collide with the Eurasia Continent that held the German Basin.

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4. Jurassic of Jordan

Jurassic rocks in Jordan are exposed in the area extending from Es Salt city in northerly direction to the lower Wadi Zerqa. Outcrops are found west and north of Arda Road in the dry valleys leading to the Jordan Valley, in the valley system leading from Arda village in the Jordan Valley to the East, and east of Deir Alla in the lower Wadi Zerqa dowstream of King Talal Dam. The most southerly wadi with exposures is Wadi Farush that lies about 5 km to the north of Wadi Shueib which is the valley with a perennial creek coming from Es Salt. Further to the north is Wadi Um Butma, followed by Wadi Nimr, north of the road to Arda lies the well exposed section in the valley below the road with Wadi Bin Faas`that branches uphill into Wadi Khuneizir and Wadi Ramad. Approximately 5 km further north the whole Jurassic sequence in Jordan is exposed along much of the Wadi Zerqa from its mouth to the Jordan Valley bottom to King Talal Dam (Fig. 55). Here within a zone of about 15 km in width, in a North to South direction rock exposure usually displays transition from the shallow sea into the beach area and into the intertidal flat. The shore often was lying in the area of the outcrops with rivers coming from the South and South-East to the sea in the North and North-West. Further to the south of Es Salt city Jurassic rocks were eroded before the deposition of the lower Cretaceous Kurnub Sandstone, and North of the canyon of Zerqa River they are covered by younger deposits.

Fig. 55: Wadi Huni with the whole series of the Jurassic exposed between the road on top of the upper side and the gypsum quarries next to River Zerqa. The upper road lies in the Kurnub, the river flows next to the uppermost Triassic, and the complet Jurassic section of Jordan is exposed along the slope

The Jurassic of Jordan is differentiated into six formations namely: Deir Alla, Zarqa, Dhahab, Um Maghara, Arda and Muaddi. At its most complete exposure in the slopes of the canyon along the lower Zerqa River the total thickness of the Jurassic sequence is about 440 m. During the whole time of Jurassic deposition from about 190 Million years ago to the end of Mid Jurassic approximately 160 Million years ago and probably also beyond that to about 150 Million years ago the Jordanian shelf area was continuously subsiding and deposition kept up with subsidence. The thickness of the sediments which were probably deposited during Upper Jurassic can be assumed from deposits known from the south of Israel since in Jordan they was eroded before the Cretaceous Kurnub Sandstone covered the erosion surface – as is well exposed near King Talal Dam in the Zerqa valley. During deposition of the Jurassic sediments, terrestrial sand and mud was carried into the area by rivers coming from southerly direction. Much sand arrived at the shore and at the tidal flats in the lower half of the section, while more sluggish currents transported predominantly suspended material during deposition of the upper part of the section. Along the rivers and shores forrest grew with trees and bushes predominantly represented by gymnosperms, especially such related to cycadeans while the lower vegetation mainly consisted of ferns. The stems of trees were often carried into the sea and many of them remained within the fillings of canals of the sandy tidal flats. In later times, when tidal flats were more muddy than sandy, redeposited forrest soil is sometimes recognized by the resin of gymnosperms which were washed out from it and transferred into amber. The Tethys produced relative high daily tides along the Jordanian shores, so that much of the Jurassic deposition formed under the influence of the tides acting on large intertidal flats into which also tidal canals were eroded and subsequently filled with sand.

The tropical Tethys Ocean along the Jordanian shelf sea supported a rich life that provided calcareous material predominantly produced by algae and invertebrates. Of these, only those with originally calcitic shell, such as certain bivalves, brachiopods and seaurchins remained well preserved and can be found in many layers, while aragonitic skeletons were usually altered by diagenetic dissolution and shell fillings deformed by sediment compaction. Compared to modern shores in a warm tropical environment the composition of the flora on the land in the Jordanian Jurassic was very different, since Angiosperms (flower plants) had not evolved and Gymnosperms dominated among the larger wood producing plants. Also quite different from actualistic shores is the formation of limonitic oolites which were produced by cyanobacterial activity, a feature which is rarely seen nowadays. It indicates that fresh water seeping from the ground along the shore during much of the time of deposition in Jordan had a different composition, with more Fe-ions in it than is normal along tropical shores nowadays.

Seen in a more general context, the spreading of oceanic crust in the widening Tethys Ocean as well as the split of Gondwana along the east African margin with Madagaskar –India separating from Africa and the opening of the south Atlantic with South America migrating relatively to the west had influence on Jordan regarding climate and the properties of the Tethys Sea water. These larger crustal movements of Africa-Arabia to the north in relation to India-Australia-Antarctica-South America influenced the geographic position of Jordan on the globe. Jordan has been interpreted to have had a position near the equator during the Jurassic. Its position on the globe was on the southern shore of the expanding Tethys Ocean. When India- Madagascar-Antarctica began to separate from the margin of the African-Arabian continent at about mid-Jurassic time the Tethys became circum-equatorial and connected with the ancient Pacific Ocean in the west. Thus a circum-global water exchange developed which may have influenced weather and deposition in Jordan. The gaps between the continents were filled with basaltic lava along the oceanic volcanic ridges, and coasts of the new continents moved by about 2-10 cm per year away from each other. In southern Africa, for example, associated to rifting, large masses of lava were produced in the Karoo volcanism, probably also providing some influence on the climate. Compared with the conditions in the Triassic the climate of the world changed from generally dry to warm and moist in the Jurassic. This change to a more humid climate left its imprint on the sediment, as is obvious when Triassic deposits are compared with those of the Jurassic in Jordan.

During Early Jurassic, probably at the Pliensbachian, the sea returned, and deposition along the coastal zone can be observed in Syria and Iraq on both sides of a high formed by the core of Arabia, that was in connection to the continent covering most of Africa. The shelf sea of the Arabian-subcontinent ended at the continental slope to the Tethys which is thought to still have the same or a similar position as the slope to the basin of the Mediterranean Sea. It lies on a passive margin to the oceanic crust of the Tethys and now the Eastern Mediterranean.

The six formations present in Jordan can be subdivided into cycles of rising and falling sea levels. Approximately 25 larger fluctuations of sea level are expressed by the exposed sedimentary cycles and can be recognized in the field. Characteristic to the lower portion of each cycle are deposits which formed near the shore, often connected to limonitic (iron rich) oolites, especially well expressed in the first cycles, but also encountered in several of the later ones. In the lower part of a cycle also terrestrial conditions such as deposits in fresh water or fluviatile deposits may have influenced the sediment. The central portion of each cycle is dominated by limestone with character of fully marine deposits or it reflects the influence of the open sea. A cycle commonly ends with a dolomitic bed indicating the influence of saline water during early diagenesis. Within cycle seven (Dhabab Formation) the limestone part is especially extended (thick) and represents a time when the shore was lying further to the south. Here actually several cycles may fall together and their existence would be expressed in deposits of the shore region that lay further to the south away from the Jordanian outcrops. It may be reflected in the deposits that can be found and were described from the Galala height on the Egyptian side of the Gulf of Suez and from the Gebel Maghara in central Sinai. In the upper section with cycles 9 to 25 the coastal portion often includes influence of terrestrial flora, often tree trunks, rarely thin coals seams, often plant remains, several layers holding small pieces of amber and rarely root horizons. The upper cycles from cycle 18 onward consist of deposits which may have formed under more humid conditions than the deposits before since less quartz sand reached the area.

Each cycle, idially, starts with a terrestrial bed, followed by deposits of the intertidal zone and continues to a fully marine limestone and ends in the return of land-near, often lagoonal deposits topped by an irregular crust often with ferruginous deposits in it. Within the area with Jurassic outcrops that extends from the North to the South for about 15 km, the shores commonly were encountered and the divide between terrestrial and marine conditions could be allocated. Thus, when sections in neighboring valleys are compared with each other the more southern often document that they deposited under terrestrial or intertidal conditions while the more northern were formed near the shore or well off-shore. During the whole deposition of the sediments of the Jurassic in Jordan the sea came from the N - NW, while river systems discharged sediment load coming from the Gondwana Continent in the S - SE.

Fig. 56: Triassic gypsum overlain by the red soil of the base Jurassic at Wadi Huni in the valley of the river Zerqa

The base of the Jurassic sequence is exposed in Wadi Zerqa near the gypsum quarries at the confluence with Wadi Huni (Figs. 56 and 57). Here the change from marine conditions and the establishment of terrestrial environment in late Triassic is well documented. The sea left the continental basin that was flooded by the interior sea during much of the Triassic. In late Triassic the shallow, mostly hypersalinal interior sea was only intermittendly connected to the Tethys Ocean. When the sea withdrew, dolomitic limestone, anhydrite and clay deposited and were subsequently transferred to, and covered by soil. During the long terrestrial interval between late Triassic and the transgression of the Jurassic sea that may have lasted about 10 Million years the climate changed from dry to more humid. Within the soil, pisolites of limonitic composition grew often to a size of more than 1 cm. They were formed under the influence of bacterial growth around a core and have thus concentric structure. They actually closely resemble the ferruginous pisolites which formed during late Permian in Jordan. In the sandy clay of the soil, root horizons can be recognized and present evidence for a climate that was fairly humid and quite warm, probably monsoonal. The roots mixed the bottom sediment by bioturbating it and their mechanical and chemical influence changed soil structure and chemistry. In the case a soil with roots in it was coverd up by renewed sedimentation cavieties left by the last decomposed roots filled with fine material transported by pore water. Such root horizons display a characteristic structure of bioturbation that resembles the soil with roots of extant trees as found nearby. Further up in the Jurassic section plant fossils indicate that palm farns (Cycadaceae) were common trees and bushes could have been responsible for producing the encountered strong root system.

The soil layer is called Hihi Formation according to Wadi Hihi next to the gypsum quarry on the southern side of the Zerqa River canyon. From Makhtesh Ramon in the Negev of southern Israel the Mish'hor Formation or Flint Clay is close to the Hihi in its composition. It has also been interpreted to have formed under tropical weathering that enabled pisolites to form. Pollen and spores give Pliensbachian age (approximately 185 Million years ago) to the Formation. In Jordan the upper part of the basal Jurassic layer may be included in Deir Alla Formation that begins with a hardground on which the advancing sea deposided the limonitic oncolites (pisolites) which were washed from the soil. The returning sea also formed scour canals that cut down into the soil, some of them reaching the Triassic dolomitic bed. Such a canal is exposed in the top of a gypsum quarry. It has steep sides and blocks of the dolomite covered the canal bottom along with iron-pisolitic debris and fragmented iron-oxide crusts. Next to it, the ancient soil with preserved root horizon holds the pisolites that had grown here below the original surface.

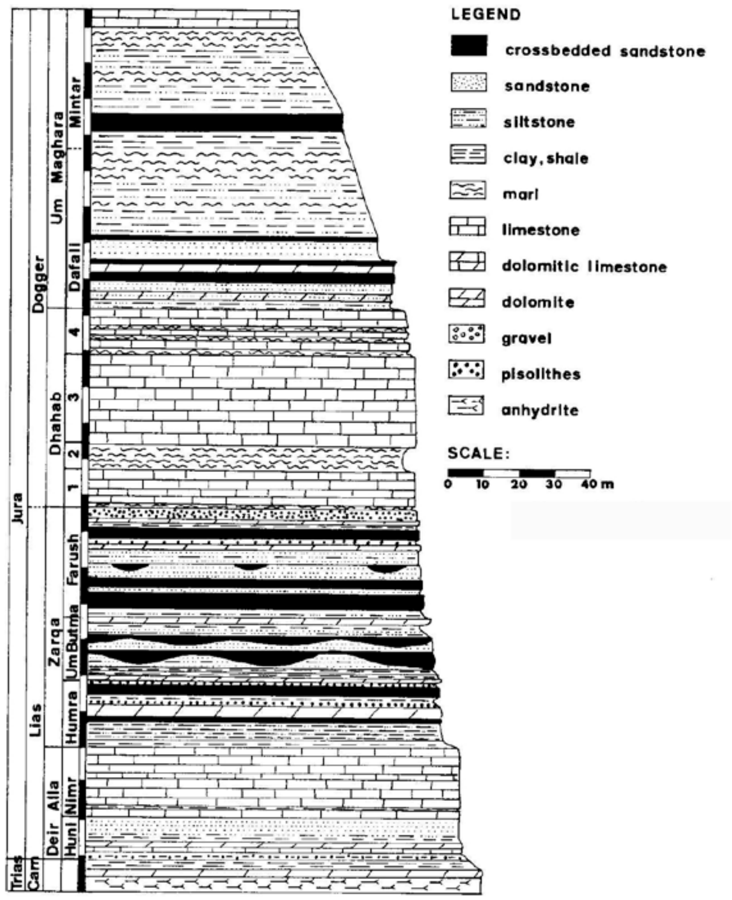

Fig. 57: Scetch of the rock column of Wadi Huni-Tell ed Dhahab section (from Bandel 1981)

Deir Alla Formation is 30-35 m thick, consists of two members (Huni and Nimr) which represent the first and second cycle and ends where limestone beds reach the sandy-silty base of the Zarqa Formation (Fig. 58). The sea reworked some of the residual soil and the first marine deposits consist of thinly bedded carbonates containing fully marine fauna with remnants of regular sea urchins (spines) and crinoids (ossicles of their stems), fillings of a small gastropod and abundant ostracods. The first cycle ends with bioturbated sandstone. About 9 km further south in Wadi en Nimr the time equivalent sandstone shows unidirectional cross bedding and represents river deposits.

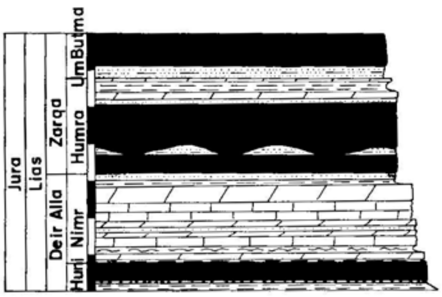

Fig. 58: Scetch of rock column of Wadi en Nimr section (from Bandel 1981, for legend see Fig.57)

Fig. 59: Jurassic in Wadi Nimr with dolomitized limestone beds of Nimr Member of Deir Alla Formation

Ostracodes can be used as biostratigraphic markers and indicate an early Liassic age of the Huni Member. Ostracoda belong to the Entomostraca of the Crustacea (primitive crabs). They modified their skeleton in such a way that the frontal portion (carapax) forms two solid valves with a median hinge. This change and adaptation of their skeleton occurred already during Cambrian. The bivalved shell holds and covers all the other part of the body including the head with two pairs of antennae and the feet consisting of three to five pairs. Ostracoda with quite similar organization as have been living in the sea since Ordovician. When land was conquered by plants they also entered the fresh water environment. Their carapax is composed of a mixture of chitin and calcite that changes into apatite during diagensis and becomes very resistent. The outer side of their shell is commonly ornamented, and the inner side may show the places where the musculature was attached to the shell. These characters and the rather rapid evolution of new species allow to distinguish many species. Due to their small size, ususally around 1 mm and less, they may occur in large numbers, feeding on microorgansims, such as algae. Most species live as benthos searching the upper loose layer of the bottom substrate for food and collecting it with their feet. Other species live swimming in the water by being propelled by their antennae, and here catch algal cells of the phytoplankton. Ostracods are thus very usefull tools for biostratigraphy.

Cycle 2 (Nimr Member of Deir Alla Formation) is about 20 m thick and consists of a series of bioturbated limestone beds with many fossils and some marls ending with dolomitic limestone (Fig. 59). In Wadi en Nimr in the South the lower limestone is sandy and contains small quartz gravel. The upper portion of the cycle consists of limestones with crab burrow network present throughout. 9 km to the North this sequence is well exposed below Tel ed Dhahab and also above the gypsum quarries upsteam of it in the valley of Zerqa River. Here limestones are without sand and quartz gravel. The uppermost beds have limonitc oncoliths and ooliths. The pure, fine grained (micritic) limestone has seams in 30 cm distance to each other. The high amplitude of the stylolitic sutures demonstrates that the sediment is composed of very fine-grained particles of purely carbonate material. A fossil-rich massive limestone with visible crinoidal fragments and crab burrows is found overlain by a black marly shale with crinoids, bivalves and brachiopods.

Thalassinoides and *Ophiomorpha* burrows represent the filling of the extensive home of crabs and in the form as found in the Jurassic of Jordan, have since been constructed predominantly in shore environments, but can also be found in areas of deep water, when abundant organic debris, such as remains of plant are available (Fig. 60). The construction of similar crab burrows can be observed in modern environment especially along tropical shores. The crab burries into the loose sediment until it reaches a depth in which the material is stable enough to stand by itself. This tube leading into the bottom is often stabilized by masonry with feacal pellets or sand glued into pellets with mucus by the appendages surrounding the mouth (as in *Ophiomorpha*). With this vertical tube the entrance to a home is established that consist of a net of horizontal tunnels deep in the bottom. These serve several purposes. The crab stores organic material collected on the surface of the sediment, such as leaves of plants or algae. The organic material stored here will change due to growth of fungi in it, until it can serve as food to the crab and its offsprings. Special chambers are constructed in which the eggs and youngs may develop, and in which the periodical molting of its skeleton can be carried out. Down in their burrow they are protected from the attack of a predator when its skin is still soft. This home needs to be washed continuously with fresh oxygen rich water and the whole system needs to be repaired after each flood or storm. Constant pumping of water into the bottom has great influence on the sediment by recharging interstitial water continuously with fresh water from the sea. The horizonal tunnel system of the crabs home often lies more than 1 m below sediment surface and therefore has a great potential of becoming preserved. In the marine sediments of the Jurassic in Jordan such burrows are very common. Preservation of this trace fossil provides clues about the diagenetic history of the sediment. Its shape and size allows reconstruction of the original composition of the sediment and its encountered final shape can be interpreted for reconstruction of the diagenetic changes afterwards, for example the amount of compaction that may have occurred.

Fig. 60: Crab burrows on the lower side of a bank of Tahuna Formation

Zarqa Formation (same as Silal F.) is fully developed along the slopes of the canyon of Zerqa River between Tel ed Dhahab up to the base of King Talal dam. Here the three members (Humra, Um Butma, Farush) represent four cycles (3-6). The base of Zarqa Formation is characterized by the first sandstones on the limestone beds of Deir Alla Formation and the top of the formation is reached with the fossilferous last iron oolite at the base of the first limestone of the Dahab Formation. The Zarqa Formation is between 35 an 75 m thick.

Cycle 3 (Humra Member) in the southern exposure in Wadi en-Nimr measures almost 25 m and consists of massive, crossbedded sandstones and intercalated flaser sand with channels. Marine influence is documented by sandstones with bioturbation. The sequence ends with lagoonal deposits turned into dolomite. In Wadi en-Nimr and Wadi Um Butma area W and NW of Es Salt *Pholadomya*-like bivalves are preserved in living position within these limestones that subsequently became dolomitized during early diagenesis. In Wadi Zerqa the equivalent beds are thinner of about 18 m, and consist of bioturbated flaser sand, dolomitic beds and ferruginous oolithe at the top. Laminated silt and shale formed in terrestrial environment cover the marine carbonates. Bioturbated and ferruginous sands, shales, and silt beds with crab burrows systems and *Chondrites* burrows, ferruginous oolites and carbonate beds mark the marine phase of this cycle.

The sediments of the southern outcrops were deposited in and near a river mouth and the sea influenced only in the upper part of the section, while in the northern outcrop the sea had more influence and it ended on a beach with fresh water seeping through it and providing the iron for Fe-oolite formation. The shore over much of the time of the cycle deposition lay between Wadi en-Nimr and Wadi Zerqa. Thus in the south river sand and gravel mixed with carbonate sand produced from ground marine shells near the shore were deposited. That deposition ended in a lagoonal environment. Further to the north lime muds formed in the shallow sea and deposition ended on the beach with iron - oolitic grains formed on the beach along which and through which ground water issued.

Fig. 61: Jurassic exposure in the Wadi Um Butma

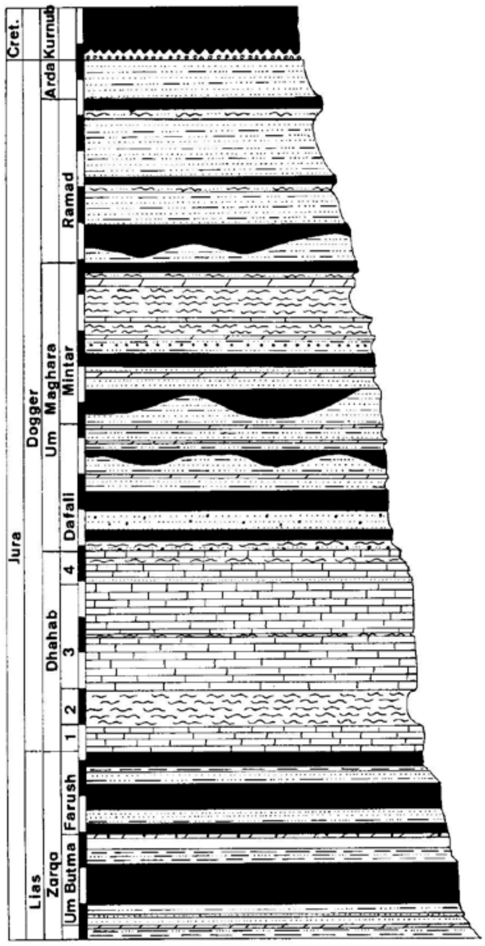

Fig. 62: Scetch of the rock column at Wadi Um Butma (from Bandel 198, for legend see Fig.57)

The bivalve *Pholadomya* represents a characteristic inhabitant of Jurassic seas. It resembles the shell shape of the *Mya* of the North Sea and like it burrowed deeply into soft bottom sediment and reached the surface by long siphons. Through them the water is pumped into the space between valves and into a cavity that holds the gills. These drive the water current and catch the cells of the phytoplankton from it by fine cilia that cover the numerous filament of its feather-like construction. Thus the gill is the feeding device of the bivalve and at the same time it is also used for gas exchange. Blood to bring the CO2 is sucked from the body through the venes of the gill, here it is exchanged for O2. The heart functions as the pump and lies in the body right next to the base of the two gills. Two pumping chambers lie on both sides of it and the blood is then pumped through the arteries to the head and the gut. The food collected by the cilia is transported to the mouth along a mucus canal, also driven by cilia. Here it is simply taken hold by lips and transported in the digestive system. Digested food is expelled in pellets with grains pressed so tightly that they might become preserved when lithification of the bottom mud is rapid, as is usually the case in finegrained limstone beds. *Pholadomya* represent a member of the Anomalocardiidae represening a group of bivalves which has almost become extinct, and its ecological place is now taken by the *Mya* relation of the Heterodonta. Due to its life deep in the ground *Pholadomya* and related species are preserved where they lived and with their valves in original position. Other larger heterodont bivalves are also preserved as internal molds, but a number of them were living in the marine sands, more shallowly burried.

Here and there also a member of the *Pinna* relation, as well as of the *Mytilus* and *Pecten* relation has become preserved. *Pinna*, as its modern representatives was attched by byssus threads in the sand, and *Mytilus* or *Modiolus* relatives, as the living mussels, lived attached by byssus to hard substrate above the ground. The outer shell layer of these as well as the *Pecten* relation is calcitic and they were thus preserved even though their inner shell was aragonitic nacre, which is usually no longer present. The effect of diagenesis is here the reason for the preservation of these fossils as brittle and with thin shell and thus difficult to extract from the rock without damage.

Cycle 4 (Um Butma Member) started after the sea completely withdrew from the studied area and coastal forrest was established. Remains of plants, especially of their root systems, are still preserved in their original position within the clay in the lowermost outcrops at Wadi en-Nimr. These beds were covered by fluviatile sands with unidirectional, 5-10 cm thick crossbeds that contain up to 3 mm large pebbles. The river carried sand and numerous tree trunks which were deposited in tidal channels. Across the fluviatile sands the intertidal flat of the sea spread out and flaser beds formed. They consist of lenticular cross-bedded sand bodies separated from each other by clay and silt partings. The top of the fourth cycle consists of sandy dolomite, indicating salinal conditions. In Wadi Zerqa the Um Butma Member measures 15 m to 24 m in thickness as a result of the local differences in the thickness of the lower sand unit (Figs. 61 and 62). The central and upper part are taken by more or less bioturbated flaser sands and the top is formed by a sandy dolomite with hardground surface and borrows (from the top), filled by ferruginous oolites. There are also ferruginous crusts here, so that the top layer is of brown to violet color. Ferruginous crusts formed within the sediment and originated when water tables changed their position in the sands. Regression of the sea is indicated by a bored hardground encrusted with ferrruginous material. Cycle 4 reflects a similar return of the sea, its establishment on the tidal flats in the North, and withdrawal here with the formation of hard ground surface, and near beach conditions with Fe-oolite forming as seen in cycle 3.

Fig. 63: Jurassic in Wadi Farush with the Kurnub cutting off Arda Formation following the bedding of the Jurassic with Ramad Member of Maghara Formation in the valley bottom.

Hardgrounds form on the sea bottom during deposition and they turned loose sediment into rock before actual rock formation (diagenesis) could take place. The special composition of the encountered hardground with dolomitic cement and ferruginous crusts indicates formation near the beach with periodically fresh water issuing through the sand. Thus former salty pore water was exchanged with fresh water and vice versa. Iron is commonly dissolved in the groundwater as sulfate and calcium-carbonate in the sand are drived from eroded shells coming from the sea. Transformation of $CaCO3$ into dolomite with about 30 % of magnesium indicates saline conditions. But these changing conditions between influence of fresh pore-water exchanged with such of saline pore water did not prevail throughout, because the holes in this hardground were probably only produced by boring bivalves, or by crabs.

Cycles 5 and 6 (Farush Member) in the south consist of 23 m of sandy predominantly fluviatile deposits with some quartz pebbles exposed in Wadi Farush and Wadi Um Butma in the south (Fig. 63). In Wadi Zarqa they have similar thickness and are predominantly sandy but with more bioturbation and with ferruginous hardgrounds. The marine phase is represented by a dolomite bed with iron oolites above and rich marine fauna of molluscs, brachiopods and corals. A thin layer lies in the top of cycle five.

The Jurassic sea during the deposition of the top layer in cycle 6 was inhabited by quite a number of gastropods belonging to different groups. Their preservation is not good since the original shell was aragonitic and was dissolved during a relatively early stage of diagenesis. Shells were missing usually before compaction was completed in the marly sediments and therefore, the internal fill of shells were also deformed. In more pure limestones they have become dissolved and the cavity thus formed was filled with calcite. Among the archaeogastropods slit-bearing shells of the the character as in *Pleurotomaria* and flatly coilded species of the *Discohelix* relation, without a shell slit, can be recognized. Among the Caenogastropoda, members of the Strombimorpha are characterized by the expanded, sometimes spine bearing outer lip of their aperture when fully grown, as is the case in some modern representatives of the groups such as *Strombus* and *Aporrhais*. Members of the Cerithioidea are represented with *Procerithum*-like slender and axially ribbed shells. The Heterostropha have, as characteristic lagoonal inhabitants, *Nerinea*- like species, which in case the folds on the inner whorls are still preserved, can even be determined to the species. The Acteonellidae by their short *Acteonella*- like shell shape are more difficult to place in a certain species. Since fine ornament and early ontogenetic shell portions are usually not preserved, a determination of species is usually quite impossible. Gastropods as in cycle 6 can be recognized in many of the limy deposits found in the whole section up the top cycle 21.

A characteristic bivalve here is *Trigonia* with thick shell wall, triangular outline and large teeth on its hinge which are characterized by transverse ridges on their side (schizodont). The group of the Palaeoheterodonta has nacreous shell as can be observed in the many members of the Unionidae which since Triassic time have settled fresh water and are also living in King Abdalla Canal in Jordan and in the sole marine *Neotrigonia* found in western Australia. The latter still closely resembles Jurassic *Trigonia,* in which the shell structure is never preserved but either gone completely or replaced by calcite that grew into the cavity the former shell has left.

Cycle 7, the Dhahab Formation has its type section in the limestone cliff of Tel ed Dhahab in Wadi Zerqa measuring about 50 m in thickness (Fig. 64). The formation is differentiated in a lower limestone, separated from a middle limestone by a clay and marl unit and upper limestone and marl intercalations. The base is formed by the conspicuous ferruginous sandstone of the top of the sixth cycle still within Zarqa Formation, while the top marks the end of the limestone and the begin of sandy deposits of the Um Maghara Formation. At the base marl overlies the Fe-oolite of cycle six and the following limestones bed has a hardground, as a surface, encrusted by oysters. A marly intercalation follows with many brachiopods. The limestone above wastotally bioturbated and this mixed muddy sediment was well compacted when crabs excavated their tunnel system in it. Fossils are scattered throughout the limestone and among them bivalves, gastropods, echinoids, crinoid ossicles and brachiopods can be recognized. Single and small colonies of corals and calcareous sponges are common in some layers. The sea withdrew afterwards and ferruginous oolite overlain by sandy marl and marly sand with ferruginous crust formed as well, in Um Butma area to the south, as well as in Tel ed Dhahab in the north. Here seaurchins and some ammonites occur.

Fig. 64: Dhahab Formation at Tel ed Dhahab in the valley of Zerqa River. White limestones locally transformed into brown dolomite

Corals occur relatively rarely in the Jordanian Jurassic and they never occur in reefs or larger growth units (determinations are as species of *Montivaltia* and *Thecosmilia*, both common in the European Jurassic). The Jurassic conditions are quite different from those occurrence in Jordan at present where corals can be studied in rich diversity along the fringing reef in the Gulf of Aqaba. The Jurassic species had a similar composition of argonitic calcium carbonate and similar arrangement of shell walls and septa. But it is not certain whether at the time of deposition of Dhahab Formation they lived in a way comparable to modern reef corals or rather like modern deep sea corals, with or without zooxanthellae. These latter represent unicellular algae which live in symbiosis with reef corals. They aid the coral in the deposition of the calcareous material of its skeleton and, in addtion, provide oxygen. They benefit from the coral by living in the shelter of their tissue and they are provided with mineral food from the body liquid of the animal. The feeding part of a coral is a polyp which consists of a hollow body of tissue that has interior walls (Mesentheria). These septa hold the body in its shape, and in case they are supported by aragonitic shell walls they are charcteristic to stone corals (Madreporaria). The polyp has cilia on its inner surface which can pump water into the interior. Muscles in its outer tissue layer can expell water from the interior by contraction when needed. Usually the interior filling of the digestive system of the polyp is expelled several times a day, and that way all waste products are gotten rid of. The Scleractinia of the Madreporaria have evolved from corals without shell by mid Triassic. In Palaeozoic times corals had a calcitic shell and it was suggested that they are not directly related to Mesozic and modern corals. Coral larvae have no skelton and settle on hard substrate, form a small polyp that constructs a calcareous basal plate first with six septa. From this initial individual one only may grow to lager size or several or many daughter individuals may bud to form a colony.

Calcareous sponges may belong to the silicospongia (Demospongia) as well as to the Calcarata, depending on the mineralogy of their needles. In case they secrete calcareous shell between the needles these are fused to each other and the whole structure becomes more easily preserved. In most sponges the needles are not fused by additonal deposits and the body after life decomposes leaving only tiny needles. They feed by pumping water through a system of canals in their body and extracting small particles from it.

Several ammonites on top of Dhahab represent characteristic Jurassic species with the complex suture line. Among them species determined to belong to the genus *Normannites* and the other determined as member of *Teloceras* may actually represent male and female of the same species. Both are members of the *Stephanoceras* group which characterized Bajocian time (approximately 170-167 Million years ago). The male would have had a smaller shell and lobe-like lappets on both sides of the margin of its aperture, and the female had a simple apertural margin. A characteristic feature is their ornament of straight strong ribs which emerge on the umbilical side and divide in median position on the flanks of the whorl, into two or three smaller ribs which cross the outer side of the shell. Jurassic ammonites have the attachment of their chamber walls (septa) to the inner shell wall with complexly folded saddles and lobes (suture line). The individuals from the top of Dhahab have their suture line well preserved since they represent internal fills of the chamber. The internal space of the chamber in the posterior shell, during early diagenesis, was originally filled by pyrite which later oxidized to limonite, while the original shell has totally disappeared. This represents evidence for an early diagenesis of the ammonites within anoxic environment, of which no trace can otherwise be noted in the present rocks. Ironsulfide is secreted only in a bottom substrate in which pore water was free oft oxygen. At the Triassic Jurassic boundary ammonites almost became extinct, and here, in mid-Jurassic, they have increased in number and types again, all of them had the ammonitic suture from now up to their extinction at the end of the Mesozoic time.

Ammonites represent carnivorous cephalopods with an external shell and they probably lived not unlike modern *Nautilus* (discussed with the deposits at the base of the Turonian). Ammonites differ by their rapid change from species to species so that they represent good biostratigraphic indicators and their species also had a shorter life. Even though much is known about them and a huge number of species was described and can be recognized from each other by characters of their shell, it is still unknown how many arms surrounded their mouth, eight or ten, as octopus or modern squid or many as in *Nautilus*. The beak present in their mouth is known, along with the ribbon of teeth in it (radula) but the function of it is still a riddle. Some ammonites had a large lower jaw and it is not known whether they used it only as a feeding device or also as lid to close the aperture (aptychus).

Brachiopods of the Terebratulida, such as species of the genera *Cererithyris*, and the similar *Tubithyris*, and a number of species of different genera of the Rhynchonellidae close to *Eudesia* occur, often together. Regarding the mode of life rhynchonellid brachiopods had similar requirements to the terebratulid, but both differ in shape of their external shell as well as their interior skeleton. Terebratulids have an ovoid shell without ribs, while rhynchonellids have strong fold-like ribs and a deep posterior median sinus. In the Jurassic of Jordan they lived attached to the bottom substrate by their pedicle coming from the umbo formed by the larger valve. This foot branched in the portion that entered the sediment and thus anchored the animal within the sediment in the shallow sea near the beach. Stable beaches were preferrend as indicated by their occurrence within or near layers with ferruginous – oolites. Taxonomic groups of brachiopods in general are distinguished from each other by the shape and organisation of the hole utilized by the attachment stalk in the larger valve and by the skeletal support of their spiral lophophore on the interior of the smaller valve. The lophophore is used for the filtration of food from sea water and is held in the shell interior. While *Terebratula* and relatives have a calcareous loop supporting the filter device in *Rhynchonella*-like species which were placed among other with genera such as *Eurysites*, and *Cymatorhynchia* no such skletal elements are developed. But their hinge, holding both valves together also differed regarding the position of the teeth and the grooves in which they are fitted, and that structure needs to be known in the determination of genera within the Rhynchonellida. The brachiopods from the Jurassic of Jordan, like most of their relatives, had a calcitic shell and are thus well preserved. The differences of the species to each other are often minute but when the internal part of the skeleton was reconstructed they represent good stratigraphic indicators.

Sea urchins occur relatively commonly in the limy deposits of the Jurassic of Jordan from base to top. With the begin of the Jurassic also the evolution of endobenthic seaurchins began and thus the settlement of the sediment itself. In former times seaurchins lived only on the sediment, while with the begin of the Jurassic some of them began to enter the sediment and extract their food from and in it. This adaptation resulted in quite a strong change of the shape of the corona especially regarding the arrangement of their body openings, and the shape and size of the spines. Among the echinoids that were noted from the Jurassic of Jordan *Leioechinus* for example is a regular sea urchin close in shape to *Diadema* that lives abundantly in the shallow lagoon at Aqaba, *Pseudocidaris* with characteristic bulbose spines resembles more modern *Cidaris* with its large spines, *Acrosalenia* is also a regular sea urchin with long spines which lived on the sediment surface along with *Polycyphus* and the similar *Psephechinus.* Their mode of life was (as can be noted on species with similar shape such as *Echinometra* present in the lagoon at Aqaba, which feed with their hard teeth of the so called “Laterna of Aristoteles”) on the sediment surface grazing predominantly on algae. *Bothryopneustes* in contrast has the anus in posterior position at about the middle height of the corona. It is thus one of the Irregularia and lived within the sediment, as did *Holectypus* that had the anus on the lower side of the corona. In contrast to the Cretaceous burrowing sea urchins these Jurassic species still have a round shape of their corona and not a heart shaped shell.

Dhahab Formation has as counterpart the Mahmal Formation at Makhtesh Ramon in the Negev Desert of Israel where it lies on top of the deltaic sandstones of the Inmar Formation. From it several species of echinoids, many species of brachiopods, bivalves, and gastropods and a number of species of ammonoids were described. Dahab Formation possibly includes several rises and falls of sea level which could be recognized as sedimentary cycles near the shore, which lay south of the outcrops of Jurassic rock in Jordan. Possibly the three cycles of Jurassic sediment exposed at the eastern escarpment of the Western Gulf of Suez on the Northern Galala in Egypt are time equivalent to the Jordanian Dhabab Formation, with about the same brachiopods as present in the central cycle. In Galala three cycles are developed, a lower with about 30 m resting on Paleozoic (Upper Carboniferous) sandstone with intertidally deposited sand, some lower ones with root-horizon, and some dolomitic beds as marine top. The second cycle measures about 60 m and has a similar composition, also root horizons on the base and marine limestone and marl deposits in its upper part with more fossils, such as *Pholadomya*, oysters and brachiopods, and the sands with strong bioturbation including *Ophiomorpha*. The upper cycle measures 70 m and its sandy and silt-rich deposits have bioturbation with crab burrows and vertical *Skolithos* like burrows and original calcareous layer transformed into ferruginous layers in the upper part of the cycle with small gastropods and bivalves.

On the Sinai in the Jurassic deposits at Gebel Maghara (not related to Um Maghara in Jordan, which represents ridge between Wadi en-Nimr and Wadi Quseib about 2 km to the west of Arda road) after about 350 m of alternating sandy and fossiliferous marly deposits are reported to include a 90 m thick limestone with corals overlain by clay and shale holding ammonites of the type as in *Normannites*. This also resembles Dhahab Formation as present in Jordan.

Dhabab Formation is overlains by Um Maghara Formation exposed in the area extending from 6.5 km west of Es Salt to Zerqa River and was divided into Dafali, Mintar and Ramad Members. The thickness ranges from 85 to 125 m and it is clearly set off from the Dhahab limestone by the appearance of sandy beds, and continues at the base of the massive sandstone of the base of the Arda Formation (exposed as base to the section in Wadi Bin Fa'as above the town of Arda and parallel to the road down to Jordan Valley).

Cycle 8 and cycle 9 are the Dafali Member as developed in Zerka River canyon. Here it is less sandy than at the type section in Wadi Dafali that enters Wadi Um Budma where it is about 35 m thick. The sandstone consists of large crossbeds in its lower part, containig some layers of quartz, gravel and some tree trunks and above flaser beds, some of which are bioturbated. The top is a sandy dolomite. In Wadi Zerqa, cycle 8 has more marl and ends with a dolomitic bed. Cycle 9 is of similar composition in its southern exposures but has iron-oolitic beds at the top. In Wadi Zerqa the lower part is sandy marly with much bioturbation and the upper beds are marly with rich marine fauna of brachiopods and oysters ending with a bank of dolomite. Both cycles have river deposits on the base covered by near-shore and tidal flat sediments and a dolomitic bed at the end. In addition the marine phase in cycle 9 provided a good environment for a shore fauna of brachiopods anchored with their pedicle in the sands and calcitic bivalves living on the muddy sandy ground.

Cycles 10 to 13 can be recognized in Mintar Member of more than 40 m in thickness. The tenth cycle is massive sandstone at the base, that in the southern outcrops fills up to 50 m wide channels with trunks of trees, quartz conglomerates and layers of mudballs. The sands above are bioturbated and the cycle ends with a dolomite bed. Thus, large tidal channels that were cut into intertidally deposited sands are here recognized, and 12 km to the north the beds of equivalent age are represented by thick sandstone and fossiliferous marl above with brachiopods, bivalves (oysters and pectinids) and crinoids.

Oysters represent bivalves with solid predominantly calcitic shell that may be quite variable in the shape of its valves among individuals of the same species. The left valve is usually deeper than the right valve and it is often attached to the substrate while the flatter right valve rests on it like a lid. Valves are connected to each other by a large organic ligament that, after decomposition, leaves the ligament groove in the hinge. Shell margins are often folded and drawn out into thin and sharp marginal edges consisting of sheets of lamellar calcite. Oyster-like bivalves with thick calcitic shell are represented by several species of *Eligmus* with strong fold-like ribs, also the curved *Gryphaeligmus*, the ribbed *Actinostreon,* the large and curved *Africogryphaea* and the small *Nanogyra.* All were attached, during early life, and often rested freely on the sediment during later life, as is the case with many living oyster. *Eligmus* is usually not interpreded to belong in the relation to the oysters, but its calcitic lamellar shell is similar to that of the oysters and indicates differences. The oysters from the Jurassic of Jordan resemble modern *Ostrea* and their relation that lives with a number of different species on the hard substrates on the beach and near to it in the Gulf of Aqaba. The Jurassic *Gryphaea* in contrast is a rather characteristic genus of that time with almost symmetrical horn shaped thick right valve and concave left valve. Ostreidae and Gryphaeidae have begun their species evolution during Triassic. The differentiation of species and genera within this group of bivalvia is difficult due to their variable shell shape, in addition to their being attached to the substrate throughout or at least a part of their life cycle. The living environment of the *Ostrea* relation in the Jurassic of Jordan lies predominantly not far from the beach, often near to that of the brachiopods.

Cycle 11 consists of basal flaser sands with some bioturbation and tidal flat deposits and above them marly deposits with an iron-oolite bed as top. In the north only marly beds are the equivalent to the southern occurrences. The 12th and 13th cycles consist of marly deposits each crowned by a dolomitic lagoonal limestone bed. Further north both cycles merge in marly beds with long feeding burrows of *Rhizocorallium* type of backfill structures. In the Huni slope of Zerka River the limestones contain rich fauna, and the limestones deposited at the top of each cycle were subsequently dolomitized.

Ramad Member of Maghara Formation in the southern outcrops (Wadi Um Butma) consist of sandstone, 45 m in thickness. The upper part of this sandstone probably forms the base to the well excessible and complete outcrop of Jurassic rocks just east of Arda in a valley below the road to Amman with Wadi Bin Fa'as at the base that splits into Wadi Ain Khuneizir and Wadi Ramad in its upper portion (Fig. 65). Within this wadi system cycles 14 to 23 are exposed within about 130 m thick section that underlies the erosion surface of the Kurnub Sandstone. Cycle 14 in Wadi Um Butma (the southern outcrop) begins with a sandstone that has a dolomitic matrix, includes layers of fine quartz pebbles, and has a pattern of fishbone crossbeds. Bedding planes are commonly rippled. This basal layer was deposited in an environment of strong currents within the intertidal realm. Flaser-sands of more calm intertidal surroundings follow and are overlain by soft sandstone with thick, large-scale crossbeds and with pebble layers. Between these fluviatile beds and the intertidal sediments below, thick ferruginous crusts and califlower-like concretions formed as results of shifting ancient freshwater tables. A bioturbated dolomitic sand marks the advancing sea and found overlain by a solid sandstone with dolomitic matrix and fishbone pattern crossbeds.

Cycle 14 can be picked up in Wadi Bin Fa'as with limestone base and marl top with rhynchonellid brachiopods, small oysters and a top of bored mud pebbles. The change to the next cycle 15 is indicated by a red ironoxide crust on a yellowish massive dolomitic limestone, indicating the lagoonal phase and transition to terrestrial conditions. Three meters of claystone follow with some shell beds and layers containing remains of plants and small pieces of amber. The sandy deposits above have reworked iron crusts, plant fossils in other layers, iron crust (continuous and interrupted) beds with drift wood and some sandy beds with crab burrows and others laminated. The cycle ends with a massive limestone bed that is churned and has irregular iron stained top. To pick up this cycle 15 in Wadi Um Butma in the south is difficult since it was deposited further shore-wards within the intertidal flats with channels and sand flats with crossbedded structure. On the other side in Wadi Zerqa the conditions of deposition were more in the open sea and marly fossil rich sediments occur, which are difficult to compare, except for their change into a dolomitic massive top layer with irons stained irregular surface.

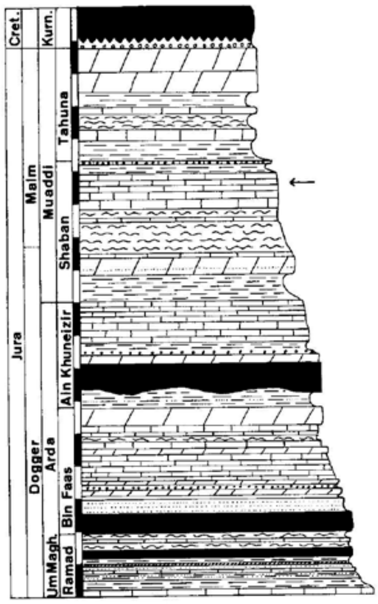

Fig. 65: Scetch of the rock column exposed along the wadi system north of the Arda road (Bin Fa’as, that branches into Wadi Ramad and Wadi Ain Khuneizir) and Wadi Shaban, above the arrow (from Bandel 1981, for legend see Fig. 57)

Arda Formation is between 55 and 70 m thick and is divided into two members, Bin Fa’as and Ain Khuneizir. The lowermost bed is flaser sand with sand filled channels excavated from cavities containing drift wood. In Wadi Um Butma this sandstone forms the top of the Jurassic sequence and is overlain by Kurnub sandstone of the Cretaceous. In Wadi Bin Fa’as above Arda dolomitic sand and a layer with ferruginous oolite follows. Tthis sequence forms cycle 15 from fluviatile sands to lagoonal deposition and again the beach.

Cycle 16 is part of Bin Fa’as Member and consists of fossiliferous limestones and marls deposited seaward from the beach in the area now in Wadi Zerqa. Fossils preserved here are oysters, pectinids and sea-urchins predominating in some layers, and terebratulid and rhynchonellid brachiopods in others. All skeletal remains of the many bivalves and gastropods which also lived here but had an aragonitic shell were decalcified and their fillings became distorted by compaction. The marls and limestones are totally bioturbated which destroyed all original layering of the original sediment. These burrow systems which reached deepest into the sediment as crab burrow of the type of *Ophiomorpha* with walls strengthened by pellets and *Thalassinoides* with walls pushed to the sides by the claws and burrow systems of substrate feeding organisms (such as *Rhizocorallium*), occur, and in more clay rich layers the branching tunnels systems of *Chondrites* are present (Fig. 66). During the strongest advance of the sea carbonate mud was deposited which was bioturbated and indurated and contains seaurchins, clearly indicating its deposition under fully marine conditions.

Fig. 66: Vertical burrows from a characteristic bed in Wadi Bin Fa'as above and east of the town of Arda- cycle 16.

6-7 km to the south in Wadi Bin Fa'as, cycle 16 begins above the surface of the carbonate bed that represents the top of cycle 15 and was incrusted by ferruginous deposits. Above, a sideritic clay was penetrated by 1- 2 cm thick vertical tubes forming a continuous bed between 50 to 80cm thick. The dense population of sand living worms probably exploited algal cells from an estuarine environment with a very high production of phytoplankton. Tubes resemble the *Skolithos* layer of the Cambrian also composed of vertical burrow with a single entrance. But, here in the Jurassic, the settlemts of the estuarine worms are overlain by a thin coal, and by clay deposits with plant remains, a further layer with worm tubes and laminated clay and silt bed without roots or bioturbation, probably deposited in a brackish lake. The cycle ends with a quartzitic sandstone with iron stained crusts on its pitted surface (Fig. 67).

A further thin coaly bed is found overlain by clay beds that contain marine bivalves and others with well preserved leaves, fragmented plants, and small pieces of amber. Laminatd silt and sandbeds with ferruginous crusts and with a bed in which such crusts were fragmented follow. The clay is intercalated with several hard sideritic beds and with layers rich with small pieces of amber. Channels cut into these beds show slump structure and dewatering features (convolute bedding). This documents that the sand was so rapidly emplaced that it contained much water. When this water was suddenly released it deformed the sand and developed large convolute bedding structures in it. The amber documents that nearby forrest floor was reworked and the grains of resin washed out.

Siderite (FeCO3) as a sedimentary deposit is related to fresh water, because sea water is very poor in iron ions. In connection to missing bioturbidity and fine clay deposited below and above, sidirite can be considered to had formed in standing fresh water, lake environment.

The clay and silt beds of cycle 16 hold many plant remains. In some layers large leaves are very well preserved. This mid Jurassic flora consist of Filicales (ferns) and Benettitales (interpreted as related group of cycads and *Ginkgo*). Flora from SW Sinai can present an impression of the type of plants growing in the region at that time. Here two species of the horsetails (Equisetophylla), six of ferns (Pterophyta), one cycad (Cycadophyta) and several conifers (Coniferophyta, pinetrees) were noted. Horsetails have been present since the Carboniferous, with *Equisetum*, living as well, in the Jurassic as now. This plant is characertistic to wet places and has its spores develop in a cone. Today, there are only about 25 species and all of them have upright stem with cylindrical bamboo-like construction. The interior of the stem is hollow and is interupted by nodes. Ferns can be recognized best when the branches have fertile leaves. The lacy leaves often carry the fertile part of the plant on their underside concentrated in spore capsules (sori). The spores are tiny and can be carried away by wind. On a suitable wet spot on the ground it grows into a tiny leaf (prothallus), which develops sexual organs. Here, the male organ releases many sperms which swim to the egg in the female organ when water covers the leaf. After fertilization a little fern grows from the fertilized egg. This change goes along with duplication of the chromosomes held in each cell, a double number is present in the actual plant and a single set in the spores and the prothallus. A conspicuous fern in Jordan is *Adiantum* hanging from wet limestone rocks in shaded water falls. Cycadeans are bush or tree like plants with palm-like shape and leather like leaves resembling those of tree ferns. Cycadales evolved from pteridosperms of the Paleozoic which have a foliation even more resembling those of ferns, but producing seeds. Of the cycadean species *Cycas* exists today in Jordan only in gardens while related species composed much of the Jurassic and early Cretaceous flora. Male cones contain pollen of which many thousands may be produced in a single cone and they resemble those of other gymnosperms and are transported by the wind. Bennettitean, such as *Otozamites* has leaves with pinnae resembling those found in Arda Formation was determined from the Jusassic of south Israel. Here on a central axis elongate oval leaves are arranged in regular manner, resembling those seen on some modern cycads. The rich flora from the branching of Wadi Bin Fa’as into Wadi Ramad and Wadi Khuneizir still needs to be analyzed and its components determined in detail.

Fig. 67: The plant horizon of cycle 16 in Arda Formation underlies channel sands. Branching point of Wadi Khuneizir (right) and Wadi Ramad (left).

The next cycle 17 has as base a layer of pebbles with a iron-oxide crust followed by marine marl with oysters. Sideritic beds intercalated in clay and also layers with worm tubes as in cycle 16 document changing environment from brackish to fresh water lagoons. Stronger bioturbation is succeeded by about 10 m of sand with large scale cross beds as deposited in channels in the lower part and in finely cross bedded structure as deposited on a tidal flat in the upper part. An ironoxide stained irregular crust with crab burrows forms the top of the cycle (Fig. 68).

Fig. 68: Seriesof fresh water beds to fully marine ones at the base of Wadi Ain Khuneizir.

Cycle 18 begins with clay and dolomitc sand succeeded by a thin bed of iron-oolite and more iron-oxide stained sand. These basal about 4 m of deposits formed near the beach are overlain by more than 8 m of limestones and marls with rich marine fauna of which brachiopods are well preserved. The cycle is topped by a totally bioturbated dolomite. Cycle 18 represent the upper part of Arda Formation and continues in Shaban Member of Muaddi Formation. Here nodular limestone and marly limestone were deposited with marine fossils among them gastropods, bivalves, sea urchins and brachiopods. A single ammonite was discovered representing a member of the genus *Micromphalites* of Bathonian age with simple sicle shaped ribs. It is not preserved with a phragmocone (chambered part of the shell), filled with pyrite and has thus the suture much less well preserved. Ammonites have an aragonitic shell and that was dissolved before compaction of the sediment was completed, thus deforming the remaining cast. Common are long *Rhizocorallium* burrows. The marly carbonate unit ends with beds rich in oysters and perhaps sediments of more lagoonal character. Above the sandy limestone was deposited, which was altered into dolomite during diagenesis after the sea had withdrawn (Figs. 69 and 70).

Next cycle 19 begins with a near-shore shell deposit with brachiopods and sea urchin spines, well preserved overlain by about 5 m of limestones and marls with *Pholadomya* in some layers still in living position and other bivalves of which pectinids are well preserved. A sandy massive dolomite bed concludes the cycle and belongs to the basal Shaban Formation that composes the upper 40 m of the section in the Bin Fa'as Wadi system. The massive dolomite of the top of cycle 19 is overlain by terrestrial deposition of clay, silt and and beds of siderite, about 5 m in thickness. They were deposited in a lacustrine environment. Here besides plant fragments, also small pieces of amber are common. With erosive surface, a 7 m thick sandstone deposited by a river with well preserved cross-bedding without bioturbation, follows. These basal beds of cycle 20 are overlain by a 7 m thick massive sandstone with big trunks of drift wood. The channel sands which may rapidly decrease in thickness have impressed themselves with large load casts into the top of the claystones below. On bedding planes ripples and trace fossils of the *Bilobites-Gyrochorte* type are common. They have been produced by animals which burrowed their way through the soft surface layers of the sand. In the silty portion, backfill structures of *Rhizocorallium* and irregular burrows are developed. Clay pebbles and small quartz pebbles are present as well. The first indicate that dried mud sherds were washed here, and the second that the mouth of rivers transporting the sand from the Gondwana continent were not far away. The top of the cycle is formed by a bored irregular omission surface encrusted with ferruginous material which also filled burrows and other cavities.

Quartz pebbles were the only coarser particles than sand that were carried into the marine environment of the Jurassic deposits in Jordan. Pebbles of other composition were not transported, with the exception of intraformational source, such as ironoxide crusts or mudballs. Quartz pebbles, as well as quartz sand are resistent to chemical weathering, and their presence in the rivers of that time documents deep erosion of the lands.

Fig. 69: Just above the plant bearing horizon, cycles 17 and 18 in Wadi Ramad, the northern branch of Wadi Bin Fa'as

Cycle 21 lies above the ironoxide oolite claystones which are intercalated with thin sandy and sideritic beds and are undisturbed by bioturbation. They represent fluviatile flood deposits. The sea returned and deposited limestone of which the lower 5 m are massive and nodular with all original depositional characters churned by intense bioturbation. They turn into more marly deposits with oysters and pectinids bivalves and are overalin by oncoidal limestone with gastropods, sea urchin spines and corals. The cycle ends with an ironoxide-stained shell bed. Cycle 22 has about 8 m of clay and marl on its base which are totally bioturbated and represent deposits of sea bottom. They are overlain by more than 5 m of dolomitic sand and sandy dolomite, some beds of them are coarsely cross-bedded the others biorurbated. The dolomite forming bankes of the top of this cycle were influenced by pore water of high salinity, probably formed in lagoons.

The normal marine conditions returned with the begin of deposition of cycle 23 with a bed containg many well preserved brachiopods. A 13 m thick unit of marl and limestone with onkoids follows. These are concentric pebbles composed of carbonate crusts and most probably grew under the influence of cyanobacterial crusts within illuminated shallow water. The cycle ends with a massive limestone about 3 m in thickness, which in its top part is transformed into a sparry dolomite. The lower part contains sea urchin spines and brachiopods and in part has the structure of cross-bedded carbonate sand and also burrows of crabs. Thus, in the upper part of cycle 23, the transition from shallow illuminated sea to beach with wave ripples and crab burrow and the last influence of saline lagoonal waters tranforming the carbonate into dolomitic limestone can be read from these deposits. Cycle 24 is only perserved with a sandstone with dolomitic matrix overlain by a sparry bed of dolomite at Wadi Ramad, and was subsequently eroded by the river depositing the Kurnub Sandstone above. The erosion surface is overlain by a coarse conglomerate consisting predominantly of quartz pebbles, but also some of the dolomite as below, also well rounded (Fig. 71).

The same story of deposition can be observed again in Wadi Sha'aban about 2 km further north, where 50 meters of Jurassic sequence are exposed, about 40 of which belong to younger deposits. An iron-oxide oolitic layer overlying a shell bed is composed of echinoderms and other shell debris. It is the representiative of the beach facies of cycle 25. The about 6 m of clay with sideritic beds may have been deposited near the shore in an environment influenced by fresh water, while the more than 10 m thick liemestones and marls contain oncoids and are thus products of the shallow sea. Some gastropods and single corals confirm deposition in the shallow sea. The banked oncoidal limestone with marly partings have a fauna of regular seaurchins with club-like spines (*Pseudocidaris*), also indicating rather normal marine environment during their deposition. With these beds the open marine shallow water deposition ended.

The beds of cycle 25 are overlain in Wadi Shaban and some smaller wadis between it and the Riverr Zerqa canyon by about 10 to 13 m of dolomite with beds having deeply pitted surfaces indicating perhaps carstic environment. These deposits were formed before Kurnub sands were deposited on top of them and may well represent erosion redeposits of the Jurassic top, but need to be more carefully evaluated.

On the Sinai the thick Jurassic sequence contains (in about the same position as Arda Formation in Jordan), a sequence of 210 m of sandstone and clay with coal seams. This may represent the equivalent beds reflecting a humid period within the Jurassic on the margin of the African-Arabian Continent not far from the shore of the Tethys Sea. The area of Gebel Maghara was covered by forrests in a swampy environment allowing the growth of peat beds and thus the formation of coal to a larger scale than expressed in the thin coaly layers in Jordan.

Fig. 70: Wadi Ramad, below and north of Arda road, with layers above plants, cycle 18 seen towards the Jordan Valley with the two large channel sands in Arda Formation well expressed.

Fig. 71: Wadi Ain Khuneizir (upper part of Wadi Ramad) to the north of Arada road with well exposed upper Jurassic section with Early Cretaceous Kurnub above almost conformably at the brown horizon (just on top of Shaban Member) and the Cenomanian limestones and marls above.

The late mid-Jurassic limestones are partly composed of nannofossils represented by minute, about 0.01 mm wide, discus-shaped calcitic plates. In the case when they show narrow circles formed by calcite plates they are determined as *Ellipsagelosphaea*, and when with a wider circle of plates, as *Cyclagelosphaera*. They represent skeletal elements of unicellurar planktonic algae, and of coccolithophorids which, from the Jurassic onwards increase more and more in importance in the production of lime mud. They still form periodical mass populations in the modern warm seas.

Muaddi Formation (also named Mughanniyya Limestone) is about 80 m thick and continues up to the top most layers at King Talal dam. Oncoidal marl and limestone, as is found in the uppermost part of the Jurassic sequence in Wadi Shaban, is also present in the exposure within the dam site of the King Talal Reservoire. Marine calcareous onkoids look very similar to such formed on land, but their mode of formation is quite different. It is rather the same as with ooids, which have a similar construction but are smaller.

Cycle 25 as exposed near Talal Dam begins with clay including sideritic beds and no bioturbation, representig deposits in fresh water. They are overlain by limestone and marl with layers of onkolites and many fossils, especially brachiopods, some oysters and rarely also ammonites. Bituminous shale that contains many small fragments of clear amber and continues in a fine grained limestone, which is eroded in its upper part and here dolomitized. Kurnub Sandstone overlies these fossil rich deposits, which reach Callovian age (Fig. 72). Thus the Jurassic deposits in Jordan span a time that lasted about 30 Million years from the middle of the Lower Jurassic to the top of the Middle Jurassic. While the basal deposits are present in Wadi Huni and bear fossils which indicate the time during which the sea started to cover part of Jordan, the top deposits can have been eroded, and it is well possible that the sea still covered part of Jordan during early Late Jurassic, perhaps up to 10 Million years more than can be documented from the preserved deposits.

The recognized cycles developed in the Jurassic deposits that can be worked out in much more detail than has been done upuntil now, since outcrops are very good. The stratigraphic indicator fossils for the Jurassic are represented by ammonites, and these occur only sporadically in Jordan. Compared to the Jurassic from Germany and France the sequence in Jordan begins with marine deposits at about the same time but the sea withdrew from the area earlier. Iron-oolites occur in both areas but limestones are less abundant in the early Jurassic of Germany and occur more commonly in Jordan. In Germany many layers consist of more or less marly shale and some dark limestones in the Liassic deposits. Middle Jurassic in Germany appears to be less divisible into cyclic sedimentation as is the case in Jordan, but depositional environment has parallels and commonly formed near the shore. Equivalents to the limestones of late Jurassic in Germany are not known from Jordan. Regarding the general thickness of the deposits in Jordan to their equivalent ones in time in Middle Europe no significant difference is noted. Compared to Triassic deposits, the 380 to 440 m of Jurassic deposits are much less than those of the approximately 1000 m of Triassic deposits in Jordan which were laid down also in a period of about 30 Million years.

Fig. 72: Jurassic in wadi Tahuna overlain by Kurnub sandstone with view into the Jordan Valley near Deir Alla.

In late Jurassic the area was probably still in the sea, but beds have become eroded, while they have been preserved in Israel. Early Kimmeridgian was determined from the Negev and the subsurface of northern Israel and also in Gebel Maghara of central Sinai. During Kimmeridgian the Indian Ocean crust started to form and spreading was going on between India- Eastern Gondwana (Antarctica and Australia) and Africa-Arabia- Western Gondwana. Gondwana is reconstructed to have rotated clockwise so that at around 153 million years ago (Kimmeridge) the paleoequator passed through Amman.

Volcanism in late Jurassic and early Cretaceous may be connected to the reactivation of the passive margin of the Tethys ocean. Connected to it, the rise of the land that occurring at Jurassic-Cretaceous boundary can be explained. The regression of the sea from the area of Jordan needs not to be connected to that rise since this regression, at the "Wealden" boundary, is found also on the other side of the Tethys, widespread in the area of the former continental sea that was present over much of Middle and Western Europe.

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5. Lower Cretaceous of Jordan

The Kurnub Sandstone is the representative of the Lower Cretaceous of Jordan, but in the South the term Kurnub has also been used for Upper Cretaceous deposits formed near the shore. Kurnub Formation is characterized by soft and colorful, often purple, more or less consolidated sandstone and is found over most of Jordan territory with outcrops overlain by the carbonates of the Late Cretaceous. The base of Kurnub Sandstone, in contrast to its top, lies on rocks of quite different ages usually in unconformable position. The Kurnub Sandstone crops out in the area extending from the valley of Zerqa River in the North to the escarpment of Ras en Naqeb in the South and is encountered in most of the subsurface of Jordan. Even south of the highest mountain range in Jordan along the Ras en Naqeb single occurrences are connected to local graben structures such as at Jabal el Ammar and within the ranges a few km east of the coast of the Gulf of Aqaba included within the crystalline Precambian coastal range. Along the Zerqa River the Kurnub Sandstone measures approximately 320 m in thickness and can be distinguished into the four parts. The lowest of these, King Talal Formation, measures about 40 m and consists of sand that was deposited by a river in its estuarine portion near the sea. Into the delta fan canals had been eroded of which some were filled with coal. The central Rumman Formation measures more than 120 m with its sands mostly deposited by a river, or sometimes by wind. The Amber Formation consists of about 55 m of mixed silt, clay and sands deposited in an estuarine to lagoonal landscape with beach bars as well as forested marsh. Here trees produced a resin that turned into amber which is preserved nearly in place and is, as well, enriched in secondary deposit. The final, Jerash Formation, consists of more than 100 m of predominantly fluviale sand and some dune sands. Common are sand filled canals, and some dolomitic beds which present evidence of the influence of the sea, becoming more important near the top where glauconic beds appear. The sequence was predominantly deposited by rivers transporting quartz sand from the continent in the SE and these deposits were influenced from time to time by the Tethys Sea that had its shore in the east and north of Jordan.

The Kurnub Sandstone received its name from Kurnub, near Beersheba in the Negev Desert. Here it was described to have more than 400 m in thickness between the eroded top of the Jurassic and the base of the Cenomanian. In its central part the ammonite *Knemiceras* was found that lived during the mid- Cretaceous. Members of this genus occur at many geographically widely different parts of the Tethys Ocean predominantly in Albian time (112-99 Million years ago). In the subsurface of Jordan the Kurnub Sandstone measures almost 70 m in thickness near Azraq in the East, about 210 m near Mafraq in central north Jordan, about 160 m near Karak in central Jordan and is thickest in Wadi Zerqa and measures about 200 m in Ajlun area. It is thus thickest between Amman and Jerash and thins to the East and South while to the North the increase of the influence of the sea on sedimentation can be noted. About 10 - 30 m are present near Batn el Ghoul in the south and about 60 - 80 m in the western escarpment at the Ras en Naqeb. Here in the SE of Jordan the age of the deposition of the Kurnub Sandstone in its upper part may differ from that in the North since it has been documented that rivers still deposited sand from the continent at a time when further North and West the sea deposited carbonate. The coast at some periods of the Late Cretaceous was lying in southern Jordan. Alomg this former shore, rivers transporting sand from the south and southeast continued to do so when most of Jordan was covered by a shallow sea in which carbonates were produced. It has been suggested to delimit the Kurnub Formation to sandstone below a horizon with the first marine bivalves, and trace fossils in the area of the escarpment of the Ras en Naqeb and to regard the sands above as deposited during the Cenomanian and later. But burrowing sea life had also left its imprints of the early sandstones of King Talal Formation which were deposited in the area of the Zerqa Valley in Northern Jordan during the Early Cretaceous.

Sands of the Kurnub Sandstone type thus represent a time-transgressive unit that appears to have covered its base at about the same time but with its top in the South of Jordan of younger age than in the North where the first fossils, such as sea-urchins, document Early Cenomanian age. Rivers still deposited sand in the South when in the North the typical calcareous deposits of the Late Cretaceous had taken over. After the start of the Cenomanian period about 100 Million years ago sand rarely reached the area of the central and northern Jordanian shelf-sea occupied by the Tethys, but the suspended clay carried by the rivers which issued in the sea in South Jordan or further to the south mixed with the carbonate.

In NE Egypt in Wadi Qena about 100 m thick fluviatile sandstone is the equivalent of the Kurnub and is called Dakhal Formation. It overlies Cambrian Sandstone and is succeeded by late Cenomanian marine deposits. Similar conditions have been proposed for the situation in the South of Jordan. These sands of Dakhal Formation had come from the south and were transported by rivers as in SE Jordan. Early Cretaceous sandstones are also known from the southern margin of Gebel el Galala forming a range parallel to the Red Sea Gulf of Suez in Egypt where they compose 80 to 100 m thick units also called Dakhal Formation. These sandstones hold massive trunks of tree ferns which occur near their base and possibly belong to the tree fern *Weichselia*. They contain crab burrows and had thus been deposited near the shore, while further to the east in Wadi Qena Dakhal sandstones have no trace fossils and are of purely fluvial character. The fern as well as the trace fossils resemble those present in King Talal Formation on the Zerqa River in Jordan.

In the southeast of Jordan the Kurnub Formation measures between 10 and 200 m in thickness and its base may contain finegrained root horizons. When the plant remains are consulted the upper portion of this formation was found to have been formed under more humid tropical climate since it contains a flora that consists solely of leaves of angiosperms and had been deposited in Cenomanian time.

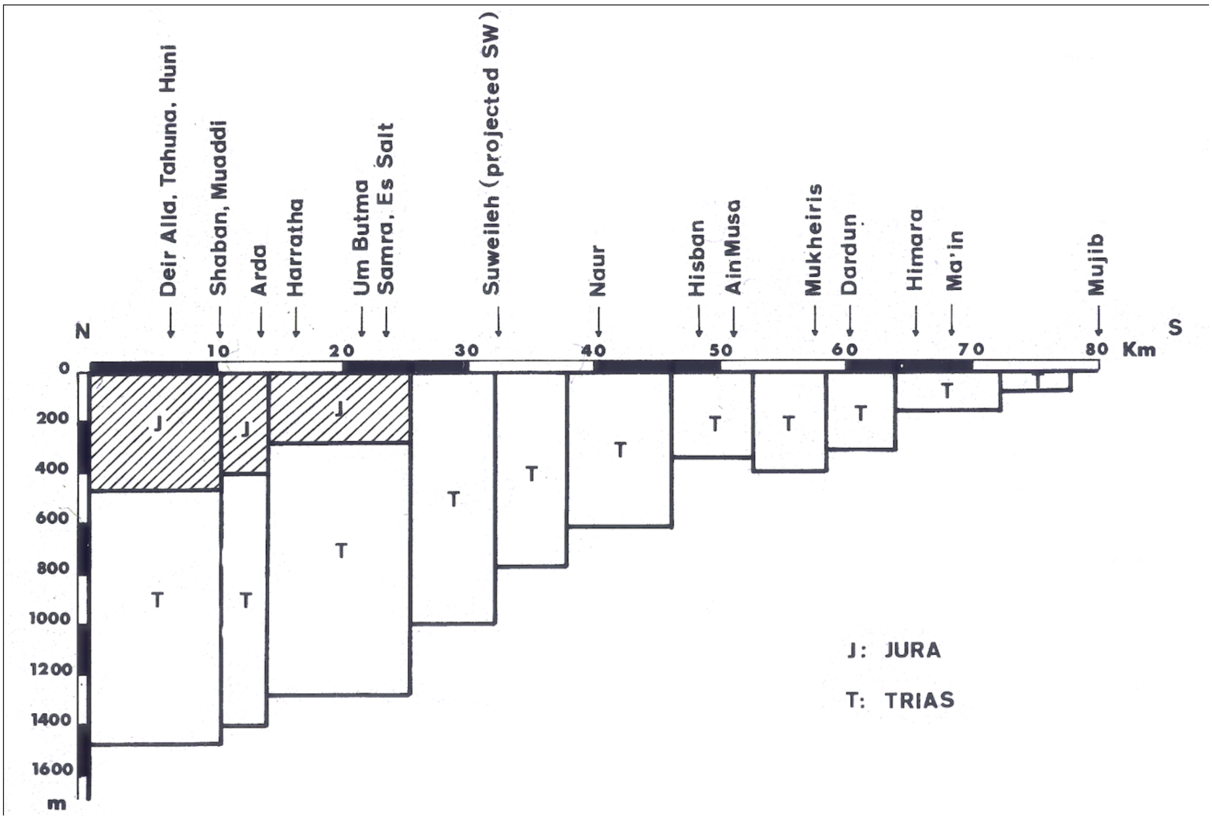

Fig. 73: Erosion surface at the time of beginning deposition of fluviatile sands of the Kurnub, as found in the outcrops from the Wadi Zerqa to the Wadi Mujib. In places in Jordan 2000 m of sediments might have been eroded between the end of the Jurassic and the begin of Early Cretaceous sedimentation.

The Kurnub Sandstone at Wadi Zerqa which is well exposed near King Talal Dam overlies Mid-Jurassic limestones of Callovian age of the Tahuna Member of Muadddi Formation with a slightly angular unconformity. Further south at Wadi Shaban, the Kurnub Sandstone overlies Jurassic beds that belong to a sequence that is 80 m below the Tahuna, also with almost conformable boundary. The former erosive surface is here often connected to quartz pebbles in the basal sands, where springs may issue, as is the case in the small Ain el Khuneizir on the Arda Road. Springs near the base of the Kurnub are very evident in the mountainous slope East of the Dead Sea where porous Kurnub sandstone overlies well cemented Triassic sediments. At these springs *Phoenix* palms grow and their green in the desert colors of the bare rocks is quite a marker. In Wadi en Nimr and Wadi Um Butma below Arda road (leading from Arda to eastern Es Salt), the boundary is more difficult to recognize since here Kurnub Sandstone overlies Mid Jurassic sandstone. In the subsurface in Azraq (central east Jordan) Kurnub Sandstone lies on Triassic sandstones, thus in similar position as is exposed on the eastern slope of the northern Dead Sea. In the Risha area (north-east Jordan) it overlies Jurassic limestones as exposed in the slope below Arda Road and in the escarpment east of Deir Alla. At Wadi Naur it is the Triassic UmTina Formation of Ladinian age that forms the base. At Wadi Hisban and Wadi Ain Musa, further south, the Kurnub Sandstone overlies quite conformably Hisban Limestone, sometimes with a gravel bed at the erosive boundary. Here a dyke of volcanic rock had been truncated. At the time, when that happened the basaltic rocks were deeply weathered documenting that it had been exposed for a long time before it became coverered by sands from the river. Further south in Wadi Mukheiris the Triassic rocks below have been transformed into a soil horizon with traces of roots before becoming covered by the basal Kurnub sands. At Wadi Zarqa Ma'in only very little of the Triassic deposits remained and the hot springs here issue from the base of the Kurnub. At Wadi Mujib Kurnub Sandstone overlies with the appearance of conformable deposition the Cambrian Sandstone. Further south in the area of Petra the boundary lies on white sandstones of Ordovician age. This boundary is so indistinct that the older deposits had been assumed to belong to the Kurnub Formation. Along the escapment of Ras en Naqeb later Ordovician Formations form the base and near Wadi Batn al Ghul in the SE of Jordan Kurnub Sandstone overlies Late Ordovician sandstones and even Early Silurian Batra shale. The position of the early Cretaceous desposits on top of sediments of such different age is an indication of a long pre-Kurnub history of rock erosion. It also documents that the region during erosion most likely had the shape of table mountains in which strata were not inclined and that it became a flat country before Kurnub sands were deposited.

During Late Jurassic the sea retreated from Jordan and the land had a relatively flat surface, at least in the area of North and Central Jordan. Since the rivers coming from the area of southern Jordan carried predominantly suspended load during later Jurassic deposition, this region was probably also a forested plain. In Europe the latest Jurassic and earliest Cretaceous were also marked by strong drop of sea level which resulted in the deposition of the Wealden beds by rivers, in swamps and in lakes on the land. Magmatic activity occurred during this latest Jurassic and earliest Cretaceous times when in Jordan basaltic rock intruded to form sills and dykes often encountered in Cambrian and Triassic sequences from Wadi Naur in the North to Wadi Mujib in the South. The dykes are easy to distinguish since basaltic rocks cut through sediments usually in a perpendicular way. They are thus younger than the sediments and of clearly volcanic origin, but the age of their implacment may differ. Those formed during late Jurassic- early Cretaceous time can not easily be distinguished from those that entered the rock column much later, during late Caenozoic time. These intruding Dykes have, indeed, become mixed up with each other. They can occur side by side in the area of the mountain slopes East of the Dead Sea. The older ones have been truncated by erosion, before the deposition of the Cretaceous sediments of the Kurnub Sandstone, as can be seen in the lower Wadi Hisban. Here the weathered nature of their composition below the base of the Kurnub Sandstone provides evidence for an extended time between their eruption, truncation and the deep reaching chemical erosion, before deposition of Kurnub Sandstone.

Sills may even be more confusing because here basaltic magma had squeezed itself between sediments and may form continuous layers of quite the same orientation as the beds of the sediment. Such sills can be observed very well in the valley below Naur and have here intruded into the Triassic strata. The basalt may resemble a pillow-lava that usually gets its characteristic structure when magma flows out from its vent below a column of water in the sea. But in the sill the base and top of the basalt has baked the sedimentary rock when it intruded them. This contact metamorphosis is only a few millimeters to centimeters thick and it clearly documents that magma entered a sediment column and did not flow onto the sediments in a Triassic sea. It is quite possible that the magma squeezed between the Triassic layers when their position was not far from the erosional surface and here it came in contact with groundwater. This would indicate, that intrusion occurred after the sequence above had been eroded off and thus quite some time after the end of the Jurassic and shortly before the deposition of Kurnub Sandstone began.

To the west of the Jordan River volcanic deposits (Tayasir volcanics) occur near the town Tayasir that lies to the west of Ajlun in the Samarian hills about as far from the Jordan River as is Ajlun, but on the other side of the river. Here more than 200 m of tuffs and basalts were reported to overlie Jurassic rocks of Callovian and Oxfordian age. Further to the north in the Mount Carmel region near Haifa volcanic rocks of Early Cretaceous age are also present. The Tayasir volcanics have been determined to be of Berriasian-Valanginian age. Volcanic deposits of early Cretaceous age have also been encountered in the Negev region in southern Israel, and basalts also compose parts of the Lower Cretaceous sequence in the Palmyrides in central Syria. At Tayasir the volcanics are reported to be intercalted and overlain be the Kurnub (Hathira) Sandstone.

Faults disrupted the sedimentary sequence in Jordan without much inclination of strata. The great hiatus present between Mid Jurassic rocks on the one side and early Cretaceous on the other indicates an extended period of non deposition in Jordan before the begin of Kurnub sedimentation. Only in one exposure a clear erosional disconformity was observed with inclined strata below the Kurnub base, and that is exposed to the north of Naur west of Amman. Here inclined Mid Triassic rocks are truncated. But even here, and just to the south of that stucture, Kurnub Sandstone overlies the Triassic strata with its characteristic stromatolite beds exposed well almost conformably. The fault bound erosion of older strata in a southwards ascending staircase (step) faulting is developed in Jordan as well as west of the rift in the Negev. The amount of deposits that must have been eroded at that time can be calculated for the area just south of the exposed Jurassic around Es Salt. Here more than 400m more likely around 450 m of Jurassic sediments were eroded before the area could be covered by the fluvial sand near to a delta. The closeness of the sea and deposition at about sea level is documented in King Talal Formation.

Further to the south, erosion removed Permian to late Triassic rocks along the Dead Sea and Cambrian to Ordovician sandstones in the south. Thus a sequence of about 1000 m of Triassic deposits was eroded. Along the Ras en Naqeb and the coastal mountain range the to Gulf of Aqaba a similar thickness of Paleozoic rocks have been eroded before Cretaceous deposits formed on that surface. The mountainous to hilly landscape was an area of table mountains which could have reached a maximum height of slightly more than 1000 m above sea level. It was eroded to form a flat plain close to sea level before the fluvial and wind driven deposition of sands began, that covered all Jordan at the begin of deposition of the Kurnub Sandstone. But during the time that lasted from the Kimmerigian of the Jurassic to the Hauterivian of the Cretaceous, Jordan was not only uncovered from the sea, but it turned into a hilly, even mountainous region. During these approximately 20 Million years the sea withrew and mountains formed and were eroded to sea level.

In Jordan exposures of the base of the Kurnub Formation from Zarqa River to Mujib river document that late Jurassic and early Cretaceous erosion removed Permian to Late Jurassic sediments of about 1500 m. But since Jurassic deposits were laid down near the shore, their original thickness further south, to their extant outcrop area, was probably much thinner than in the area north of Es Salt. From the Negev Desert at least 500 to 700 m of erosion have been calculated.

In early Cretaceous times the circumequatorial Tethyan Sea separated the Euamerican region and the Asian Block as huge continent on one side from the African-Arabian Plate and the South American Plate (still connected to Antarctica) and India with Madagascar on the other side. The time of structural unrest, mountains building und their subsequent erosion before begin of deposition of the Kurnub Sandstone falls together with the larger tectonic unrest connected to the splitting up of Gondwana Continent. The South American Plate was not completely separated from the African Plate and during the Early Cretaceous only a southern Atlantic Ocean was forming. Thus plants and animals of the land were separated from each other predominantly by the circum-equatorial Tethys Ocean. Jordan thus was lying near the northern margin of the southern continent Gondwana, and a certain evidence of that place on the globe can be detected by the presence of pine trees belonging to the *Araucaria* relation, trees which are characteristic to the Southern Hemisphere.

The Kurnub Sandstones deposited on a rather flat plain near sea level. Subsurface data indicate that near Azraq marine influence during the deposition of Kurnub sandstones was low, since dolomitic beds were not recognized. Plants have been recognized in the South represented by impressions of leaves of angiosperms which were interpreted to have lived perhaps during Cenomanian time. But also the Aptian-Albian deposits of the Amber Formation in northern Jordan contains many plants and also leaves of angiosperms. With a general rise of sea level during the Aptian- Albian time, 120 to 100 Million years ago, Jordan was successively flooded by the sea and by the begin of the Cenomanian much of Jordan was permantly covered by sea, but it is still a matter of debate, at what time within the Cretaceous the sea reached Southern Jordan.

The presence of the Tethys Ocean in the west is documented by marine intercaltions found near Naur where the fluviatile sandstone is intercalated by layers of dolomitic and shaly sediment with bioturbation indicative of marine life. Also along the Arda Road and in the escarpment to the east of Deir Alla sediments indicate that northwestern Jordan had a position near the margin of the southern Tethys Ocean. The coal channel of King Talal Formation was reached by the sea- as trace fossils document. Sandstone was deposited by channels in a fluvial-deltaic system than thinned out and forked to the northwest, thus, forming a bird foot delta. Such delta was also reconstructed from subsurface data near Tel Aviv, and from the subsurface of the coastal plain of SW Israel. Here the transition from the latest Jurassic to the Cretaceous has been interpreted to lie in a sequence of shale. It is overlain by a sandy-shaly-limy oolitic complex of Valanginian to Aptian age with 700 m thickness. The Albian unit is dolomitic-limy, chalky-shaly, and holds detritic layers of 320 m thickness.

During the deposition of the Kurnub Sandstone in Jordan a revolution in the life history of the Earth occurred with the evolution of the flowering plants, Angiospermata. In the King Talal Formation of the Kurnub Sandstone ferns and other sporophytes (*Matonisporites*) were documented. These spores closely resemble the spores of modern *Matonia,* that has been interpreted to be a relative of the Cretaceous tree fern *Weichselia* and also *Cyathidites* that resembles the spores of modern tree ferns. The pollen *Monosulcites* may come from *Cycas* relation, *Inaperturopollenites* can be of the Araucariacea relation, both representatives of the gymnosperms. Spores and pollen were extracted from the Kurnub Sanstones near the king Talal Dam and indicate an age of deposition that was before angiosperms appeared.

The palynoflora of Amber Formation (spores of ferns, and pollen) in contrast, also holds pollen of Angiosperms. But it is characterized by the dominance or abundance of pollen produced by the two conifer families Cheirolepidiaceae (*Classopollis*) and Araucariaceae (mainly *Araucariacites*). The Cheirolepidiaceae are drought-resistant conifers which prefer warm temperature and have grown in low-lying coastal environments. Pollen of Araucariaceae suggests that araucarian forest may have been situated landward of the cheirolepidiacean belt.

The plant revolution lead to the evolution of the flowering plants which with their diversity of over 250,000 species are the dominant vegetation in most terrestrial ecosystems. The earliest fossil records of Dicotyledones (flowering plants with two leaves emerging from the seed) are 127 to 125 Million years old as is determined predominantly on the basis of pollen. The basal eudicots (flowering plants) were already present and diverse by the latest Barremian and earliest Aptian. A basal eudicot family is for example represented by members of the Ranunculacea which are still quite common in Jordan flowering in the spring time. *Monocolpopollenites* would indicate the presence of palm-trees, as well *Monosulcites*, (both Monocotylendones that is flowering plant with one leave emerging first from the seed) *Clavatipollenites* is assigned to the Magnoliacea, and both types have been recognized from the Kurnub Sandstone along the Zerqa River.

King Talal Formation of the early Kurnub Sandstone as exposed next to the Talal Dam begins with well sorted fine quartz sand that overlies the Jurassic limestone of Tahuna Formation with a slight unconformity. About 20 m with large unindirectional cross beds of fluviatile character follow. Individual sets are graded from bottom to the top as is found in fluviatile environments of an estuarine river near its entrance to the sea. Above that sequence a channel is exposed that is about 4 m deep and 50 m wide (Fig. 74). It is covered by fluviatile sands in large cross beds resembling those present below. Laterally to the channel deposits the sand settled with marine benthic life. The alluvial plains next to the channel supported a rich growth of herbaceous and tree-like ferns (pteridophytes), mainly consisting of *Weichselia*.

The bottom of the channel is flat and is covered by angular debris that had been scoured from the sediment during its erosion. Weakening flow caused wood debris to settle within the cross-bedded sand. Tree trunks and fruit-cones of cycadeen plants can be recognized. Stems of the tree-fern *Weichselia* are the most common logs. A fine lignitic mudstone that once represented an organic ooze fills most of the channel and has been transformed into coal. At the margins of the channel sandy and silty beds preserved the fronds of *Weichselia*. The primary pinnae still retain their original convex concave shape, but stems are always compacted and strongly incoaled and both stems and leaves are well preserved and bear no traces of long transport. The tree fern *Weichselia* has thus grown very close to the margins of the channel, but not directly on its banks and within the shallow portions of the channel since there are no traces of roots preserved here.

The tree-fern *Weichselia* had been reconstructed with a special root system resembling aerial prop roots as are found among such plants that nowadays grow in the tropical mangrove forrest. *Weichselia* grew along the northern shore of Gondwana and has been reported from late Jurassic to late Cenomanian. This plant, common in estuarine swamps, occurred on both shores of the Tethys Ocean, and along the shores of its shelf seas that covered parts of Africa and Europe prior to the appearance of the modern mangrove that is dominated by angiosperm trees and bushes.

Leaves and cones of a member of the Cycadales (Cycadaceae) are preserved in the channel-fill. These cones have a central axis and numerous spreading structures, the scales, which are modified leaves arranged around the axis in a low spiral. Each female cone (sporophyll) has the seeds attached directly to the stalk. The outer surface of the cone has a rhomboid scale pattern similar to modern Cycadean cones with hexagonal scale and resembling the cone of a pine tree. Cycad leaves are carried in a crown which terminates the trunk, and similar single leaves as of a *Zamites* like, frond with nearly parallel veins, occur in the deposits of the channel. *Weichselia* associated with *Zamites* and *Brachyphyllum* was described also from the early Cretaceous of Lebanon. Plants of the extinct groups, for example the Bennettitales and Caytoniales have similar leaves with modern cycads, and the shape of their stomata in the epidermis could help to distinguish these from each other.

A fern closely resembling modern Polypodiaceae has also been encountered with fragments of fertile fronds which still bear their spore capsules. The spores that have been extracted and determined from the sediment belong to several ferns which may have grown in moist surrounding under warm conditions either in marshes, along riverbanks or in the shelter of larger trees in forests.

The top layer of the channel is a well bedded sand bed with bioturbations of crab burrows of the same type as in lateral position to the coal filled channel. Muddy sediment had been transported into these sand beds from below by the crabs when they excavated their burrows. Aside from numerous well preserved burrow systems of different crabs also the trails of bivalves are common along with a number of other trace fossils indicating that a rather diverse assemblage of marine animals have lived here and left their characteristic resting marks and motion trails. After a period of fluctuating marine and fluvial influence river flow increased, and the sand deposited on top of the channel consisted of river deposits without bioturbation. The channel formed in estuarine environement, that is in an area in which fresh water of a river and sea water from the Tethys mixed depending on the condition of the tides. The presence of well preserved plants in the deposits of the channel indicates that they grew nearby while the absence of root horizons in the channel margin indicates that it was not right on the channel but a little distant from it, probably upstream. When the channel had just been eroded, first fillings occurred with relatively strong currents, while later on water was slack and fine ooze with much plant debris filled it. Later a new flood covered it with sand that was settled by marine animals which lived on the intertidal flat of which crabs and bivalves are documented by their characteristic traces. Later the fluvial sand of the delta covered the whole structure.

Fig.74: King Talal reservoir with channel bearing King Talal Formation just above the water level and below the road and Ruman Formation above.

King Talal Formation is overlain by the thick Ruman Formation (also called Subeihi Formation) composed predominantly of sand that was deposited by rivers. Large crossbeds have a major direction of the layers which indicate a derival of the sand from the SE. Ruman Formation is more than 100 m thick in Wadi Zerqa and at about the time of its deposition the world-wide floral revolution took place. In Wadi Zerqa area only sands were laid down mostly transported here by water, less commonly by wind (Fig. 75). The different modes of transport can be recognized by the size and shape of the crossbeds within the sandstone. Sand migrates by hopping over the ground, either driven by the current of the water or by the wind. The differences of the final resting place of sand grains can be well studied in Jordan, where dunes produced by the sand are present in different sizes very well in Wadi Araba, while ripples of sand transported by water can be studied in every creek and river. The most obvious difference lies in the size of the structures formed. Often very large ripples are developed in dunes which also may have a steeper slope on which the sand comes to rest, and smaller size and weaker inclination of slopes of ripples form in running water.

Fig. 75: Dune sand from the Ruman Formation near Talal dam

The sand consists predominantly of quartz grains with very few other elements and almost no feldspar. As a heavy mineral some zircon is present. Sand grains may sometimes be unaltered as is the case, when eroded from metamorphic and plutonic rock from the old Precambrian continental crust and only rounded by transport. But it has been documented that grains may in other cases show relicts of rims of former quartz cement as were formed in older, more diagenetically altered sandstones. Kurnub Sandstone is thus a mixture of sand from decomposed crystalline base and from eroded older sandstone.

After the floral revolution which occurred while sands of Ruman Formation were deposited in Jordan marine influence returned with the Amber Member of about 35 m in thickness. It consists of sand filled channels and silty to clay-rich interlayer (Fig. 76). The environment also held sand bars settled by numerous animals producing *Diplocraterion* U –like burrows in which animals lived that exploited the rich plankton of estuarine and lagoonal water. In a section exposed next to Zarqa river at the mouth of a small side creek on the northern side of the river about 5 km downstream from the road bridge Amman – Jerash the estuarine deposits are well developed and their sedimentology and fossil content can be easily studied in the field.

Fig. 76: Sandbar with U-shape burrows at the basal Amber Formation at River Zerqa

The sand bar with large scale cross beds in a several meters thick bank can serve as base to Amber Formation (Fig. 77). It can be recognized in the field since it has the characteristic large u-shaped burrows of the *Diplocraterion* type which are easily recognized. *Diplocraterion* has the same kind of construction as *Rhizocorallium* but differs by being of a vertical structure only, while *Rhizocorallium* begins as vertical burrow and later turns in horizonal. The different shape documents difference in function of the burrow. *Diplocraterion* was constructed as a home with the animal in it remaining here for a long time, perhaps the whole life, while *Rhizocorallium* was constructed when the animal mined a layer of sediment in surch of food. Here in an area with strong currents passing over the bar the sand had been settled by crabs producing the U-shaped burrows and remaining in them throughout life. During growth they increased burrow size by enlarging the U tube and coating material to the inner wall producing the inner lamination that is present between the canals of the outer tube. The crabs may have exploited the water washed across the bar by fishing plankton from it.


Fig. 77: Rhizocorallium feeding burrows from the Amber Formation

A sandy carbonate bearing layer follows with strong bioturbation indicating deposition in a fully marine environment and measures about 1 m in thickness. Above that follow about 2 m of flaser beds as forming during intertidal conditions when currents periodically change directions and ripples migrated back and forth. With slack water fine silt and clay laid down on the ripped surface. A coarse, about 1.5 m thick sand bed above served crabs to construct their burrow system of the *Ophiomorpha* type with walls of their tunnels coated by fecal pellets. Above a clay rich layer of about half a meter with many plant fragments and some amber was probably deposited in the slack water of a lagoon. Tidal flaser sand of 2 m thickness follows and ends with a sand bar colonized by sand-anemones. They left their characteristic living burrows during migration upwards compensating deposition of sand. Very similar trace fossils are present in Cambrian sandstones near the Dead Sea and document that the same strategy of living in loose sand had been living here as well.

A ferruginous crust separates the layer with the burrows from one meter sand above which formed in shallow water and settled by a rich infaunal life. The iron-oxidic crust indicates that fresh water infuenced the phase between these two banks. The marine bed fell dry and was settled by plants which left their root system. The root horizon is overlain by about 1.5 m of laminated muddy silt and sideritic beds, representing deposits in a stagnant fresh water lake or lagoon. The layer above is most important to people intersted in amber because here large pieces of amber up to fist size are found in a bioturbated dirty silty sand (Fig. 78). It was again used as soil by plants producing a root horizon. The layer above used by crabs, is about 1.5 m thick and its basal part was a near- beach rim along which a lot of amber was concentrated. The amber had rarely been bored by clams and thus documents that it was exposed to marine conditions at the bottom of the sea. The deposits above contain many plant fragment often with well preserved cuticle, among others of leaves which resemble those of modern *Agathis*. A crust of a hardground is composed of iron-hydroxide and from its surface the burrows of crabs enter the sediment below. These animals thus lived in an environment with changing salinity and fresh water at times, as is seen nowadays in the environment of mangrove forrest. But this swamp was not yet a mangove since typical mangove vegetation was to form later in time and similar forrests as today are known only from the Eocene onward. The beds above, of about 2 m are laminated silt and clay with coaly inter-layers. Here only few signs of life on the bottom of a lagoon with quiet water and oxygen depletion are noted. It fell dry and was settled by plants leaving their roots. Onto this root horizon the returning sea deposited many fragments of wood and amber. The sand of more than 1 m in thickness is riddled by crab burrows and overlain by a next deposit of amber and wood. The following silty and sandy layers are about 1.5 m thick, laminated and represent deposits in a lake that was surrounded by araucarian trees. Their leaves fell into the water as well as many fine drops of resin which turned to amber. Here the amber is in place next to the trees and the wood in which it formed for example as reaction to the attacks of insects. It is the bottom of a quite pool or dead arm of a river that was surrounded by the trees in which the amber formed. A thick sand-unit follows with undisrupted crossbeds with which sedimentation of Jerash Formation begins.

This section, in its upper part as exposed between the river and the road above, is a place where amber can be seen in the rock, amber as is also known from similar age from Lebanon, where it has provided many inclusions of a diverse fauna of insects. A tiny fly (up to 2 mm) of the order Diptera (Fam. Chironomidae) and also a male midge (Family Sciaridae of the Diptera, Nematocera) is 1.2 mm in size was recognized from the Jordanian amber, which contains more insects. The colours of the Jordanian amber range from translucent yellow to faintly translucent dark red, to brownish. Besides the clear amber other samples are turbid, beeing clouded by air bubbles or particles of small plant debris. Some of the pieces show a laminated structure that formed when individual layers of resin flow over each other in brief intervals. All pieces have a dark weathering crust. Single amber pieces may reach the size of a man's fist. Most are smaller irregularely rounded pieces measuring a few centimetres to small drops of a few millimeters.

Fig. 78: Riverbed of Zerqa with the amber bearing siltstones exposed.

During Albian time when Amber Formation was deposited araucarian conifers produced the resin. The tree responsibe was *Agathis*-like as is documented by leaves with the characteristic structure of the cuticula and construction of the wood. Araucarian pine trees represent an ancient conifer family that was widespread in both hemispheres during the Mesozoic, while their three extant genera *Agathis, Araucaria* and *Wollemia* are restricted today to the Southern Hemisphere with most species living in the Indomalayan and Australasian (Australia, New Guinea, New Caledonia, Norfolk Island) areas and two species of *Araucaria* occur in South America. *Araucariacites* pollen have been recognized from the sediments of the Amber Formation and the leaves found here are of the type as found among modern *Agathis*.

Some pieces of large amber pebbles are found bored. The boreholes have a club-shaped outline quite like those excavated by modern bivalves of the Pholadidae. Normally these bivalves bore into solid mudstone or lignite (*Pholas* etc), wood (*Teredo* etc) or stone (*Martesia*). But it has been reported that *Martesia* and the related *Xylophaga* may also attack a variety of plastics. In Hong Kong waters a species of *Martesia* is capable of tunnelling into polyvinyl chloride tubes. This material can not be dissolved by weak acids or alkalis. The bivalve therefore bores strictly mechanically. In a similar way of mechanical boring without the help of substrate softening bacteria as in the wood boring bivalve *Teredo* was utilized by the Cretaceous pholadids to penetrate the amber. The bore-holes have the same size and shape as those found in modern plastics.

The activity of wood-boring bivalves such as modern *Teredo* in the sea is documented by drift wood riddled by holes encountered in the Jerash Formation of the Kurnub Sandstone (Fig. 79). Modern wood can be bored by *Teredo* which have reduced the size of their shell and use it a boring device. The body extends in worm-like shape with the mantle area expanded posterior of the shell and the siphons are thin and can be withdrawn. When a pelagic larva of *Teredo* meets drift-wood in the sea and is ready to take up benthic life, it attaches with an organic thread (byssus) to the wood. From here on it drills into the wood by a combination of mechanical boring activity with the foot and the shell, and biological activity aided by wood devouring bacteria. These are concentrated in the mucus secreted by the bivalve and they loosen the fibres of the wood by digesting cellulose fibres. The shell of *Teredo* is modified during growth to act as raspling organ which can be rotated to detach wood fibres made weak by the bacteria. These detached particles are carried to the mouth and together with algal cells filtered from the sea are eaten. The bored tube will finally be coated with a layer of calcite, depending on the size of the settled piece of drift-wood and the number of borig bivalves at work in it. As soon as their burrows come into contact with each other the calcite coat on the inner side is formed. Such tubes may be short or in the extreme up to 1 m long and they may have a diameter of up to 1.5 cm. Since they are of calcitic composition they have a rather good chance to be preserved in the paleontological record, while the small aragonitic shell of *Teredo* as well as the wood have less preservation potential.

Fig. 79: Amber Formation next to Zerqa River (lower left) and the Jerash Formation above it with large sand filled channel exposed in the upper left.

The upper Kurnub Sandstone is taken by Jerash Formation of about 130 m thickness and consists of channel sands intercalated with thin silty beds and clay fills of channels both of which hold plant remains and trace fossils. A bed within the equivalent of the Amber Member or of the basal Jerash Formation expposed to the west of the Zerqa River near the road from Es Salt to Deir Alla has provided the ammonite *Knemiceras* documenting the Albian Age of these deposits and this age has been confirmed by pollen and spores. In Wadi Salihi near its confluence with King Talal Lake the uppermost Kurnub Sandstone consists of dune sand. Here in the depressions between the dunes the imprints of the feet of large dinosaurs are preserved. Thus these large reptiles roamed the river shores and the shores of the Tethys in Jordan as well as in many places on Earth and fed on the trees and bushes.

To the NW of Lake Tiberias in Galilee and on the northern Golan Height marine deposits are exposed and have been described. They were deposited at the same time, when in Jordan river deposits predominated. These about 400 m thick deposits of the Galilee Group have been subdivided into 5 formations (Nabi Said, Ain el Assad, Hidra, Rama and Yagur). Three pulses of sea level changes were recogized, which could be detected also in the Kurnub section as exposed in Wadi Zarqa. The first was during the Barremian and may be correlated to the basal channels in King Talal Formation, the second was during the Aptian and could have left its imprints in the Amber Formation, and the last was during the Albian and may have its equivalents in the Jerash Formation. The marine deposits are such of shallow water in the open sea and of lagoonal waters near the shore and at the shore. Indications are obtained from oolithic beds, interfingering Fe-ooides and calcareous green algae such as *Cylindoporella*. Biostratigraphical control is by orbitolinid foraminifers and ostracodes, and in the uppermost unit also by the ammonite *Knemiceras*. This platform had its rim about 40 km to the west of the Galilee sections and here during Albian to Cenomanian with rudist banks which have been interpreted as barrier to the open Tethys Ocean. Between that edge to the ocean and the fluvial deposits near the continent a rim of the Levant Platform that was about 40 km wide and can be traced from the northern Sinai to Libanon was taken by shallow sea. The coastal condition is documented by the components of the limestones, animal remains especially of ostracodes, which give evidence for brackish phases of sedimentation and occurrences of Fe-ooides which formed under influence of fresh water coming from land. Thus climate was probably relatively humid during the Barremian to Albian, while afterwards no Fe-ooides formed and lagoonal deposits were usually dominated by saline conditions.

At Jebel Ammar at the eastern margin of the outcropping Ordovician in Jordan a large sand filled channel due to its weight sank into the underlying fine silt (Fig. 80). Pillow-like bodies of sand detached from the main body of sand and sank into the wet silt below. Thus silt was pressed up into the sand beds of the channel with the water moving out and forming large convolutions. The reconstruction of two sand filled channels exposed at Jebel Ammar as glacial deposits of Ordovician age in the SE of Jordan is not convincing. In the outcrop at Jebel Ammar the channels were eroded into fine and water soaked silt. When this channel had filled rapidly with coarse sand its weight pushed into the silt-substrate below. Thus water was pressed out of the bottom substrate and channel sand locally sank into it. By this way basal sand cushions detached from the base and sank into the soft bottom substrate and water from the later was pushed up and entered the channel sand forming outflow channels. These movements of sand into the dirty fine sand below and water and silt into coarse sand above resulted in characteristic rounded shapes of loading structures and ridges and scratches formed by this convolution. These deposits have been interpreted to represent diamictites, but outside of a rapid deposition neither the light brown coarse sand of the channel fill nor the fine grained greenish gray sand of the beds into which the channels with possibly steep marginal slopes had been cut document poorly sorted consistency, as is expected from such deposits when formed by melting ice. Most probably the outlier belongs to the Cretaceous, which is more continuously exposed further to the north.

Fig. 80: Jebel Ammar with the sandstones of a smaller and a larger channel cut into soft silt- mud at Early Cretaceous times and was called Ammar Formation. (Foto Marwan Raggad)

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6. Cenomanian up to Coniacian of Jordan

During Cenomanian to Turonian times Jordan lay on the northwestern margin of the Arabo-Nubian shield. To a large part it was flooded by the southern Tethys Ocean. After the marine regression in the Late Jurassic, structural unrest and erosion, the sea during the Early Cretaceous nearly reached Jordan and only small incursions occurred along canals of the rivers that covered the plain with their sands. An intensive marine invasion occurred in late Albian/early Cenomanian and progressed South and East until by mid-Cenomanian most of Jordan was covered by sea. Regarding sedimentation in Jordan is was continuous from the fluviatile Kurnub to the marine Upper Cretaceous and from thereon until Eocene and the end of the Tethys as circumequatorial sea.

This transgression occurred during a major advance of the Tethys Ocean onto the margins of the African plate and from here on, most of Jordan remained under the influence of the shelf sea throughout the Late Cretaceous. Within the Coniacian, a change of the chemistry and probably also the temperature of the sea occurred and the depositional environment changed from a predominance of limestones and marls to that of chalks. For a period of about 10 Million years from the end of Albian to mid Coniacian the level of the sea fluctuated little while the area of Jordan slowly subsided. This lowering of the continental crust was balanced out by predominatly carbonate deposits produced in a shallow sea and on tidal flats. In northern Jordan in the Amman region about 320 m of sediment were deposited during Cenomanian and during Turonian to Coniacian about 140 m of mostly fossiliferous limestones and marls. In central Jordan Cenomanian deposition amounted to about 50 m of deposits, while it was similar to the North during Turonian. That amounts, in the region of Amman, to about 460 m of subsidence within 10 Million years of which it is quite unknown whether it occurred evenly or in different spells. In the south and south-east of Jordan subsidence was less.

A westward flowing circum-global current was established in the Tethys Ocean that was responsible for continuous warm climate during the Cretaceous. The shallow warm sea that covered much of Jordan produced predominantly carbonate sediments $CaCO_3$ extracted from sea water and secreted in large part in the form of skeletons of benthic animals, algae and crust forming cyanobacteria, and to a lesser extend of planktic protozoa and algae. The original composition of these deposits can rarely be understood without taking the processes in rock formation into consideration. A direct approach without interpretation of diagenesis has often resulted in a wrong reconstruction of the character of the former sediment including fossils in it.

On the Jordanian shelf sea of the Tethys Ocean the area in which sediments formed predominantly by the influence of the sea extended far to the south. This sea was usually shallow and it periodically withdrew from much or parts of the shelf area during periods of low water level in the Tethys Ocean or a less rapid subsidence of the margin of the African continental plate. Fluctuations of the sea level of the ocean (eustatic sea level changes) have been reconstructed on a world-wide scale, but their occurrence on the Jordanian shelf and influence on the preserved sediment is still difficult to document. The global sea level rise that has been proposed during the begin of Cenomanian coincides with the transgression onto the shelf in Jordan. Other lows and highs of the global sea level curve (allocyclic factors) are not so obvious. It has been assumed that during the transition from Cenomania to Turonian a major transgression-regression peak occurred that resulted in the deposition of unusual sediments on one side and a hiatus in deposition on the other. In southern Jordan rivers from the African Continent discharged their quartz sand load into the sea and these delta deposits were drowned from time to time. Land lay also in the east with the evidence presented by a thinning of the sequence in the subsurface to about 80 m and its total absense in the SE desert of the Sirhan depression. When the sea level rose fluvial sands were covered by or mixed with carbonate from the sea. Such intercalations are characteristic for the rock column exposed along the southernmost outrops in Jorden, in Ras en Naqeb escapmment. In the SE of Jordan rivers almost continuously discharged quartz sand and here the deposition of the “Nubian Sandstone” continued. These sandstones form a sequence that resembles that of the Kurnub Sandstone and is difficult to distinuish from it. The global sea level curve should here, in the SE of Jordan, be documented best by the back and forth of fluvial sands onto marine deposits, but it is still difficult to determin the age of the different advances onto the former delta deposits. More than five such advances of sands from the rivers onto limy deposits of the sea have been documented by studies along Ras en Naqeb escarpment in the south. On the other hand advances of the sea onto the Nubian continent went much further to the south than in the area of Jordan at some times within Cenomanian and Turonian reaching the area of the Eastern Desert of Egypt.

The margin of the Jordanian shelf to the more open ocean (western and northern margin of the Levant Platform) is in part characterized by quite pure limestones and banks of rudist bivalves. Such deposits are encountered along the northern side of Ajlun mountains in northern Jordan. In the large area between this northern edge of the shelf with the open Tethys Ocean and its south eastern continental margin carbonates produced in the sea was mixed with more or less suspended clay that were predominantly been discharged by the rivers which entered the sea. In this relatively restricted shelf area oysters are representative of the most common macrofossils, and due to their shell construction of calcite and size are also still well preserved and visible. But the most important indicators for the biostratigraphy of the deposits are represented by ammonites and coccoliths.

Late Cretaceous sediments can be studied in Jordan from the North of the area west of Irbid to the south to the escapment of Ras en Naqeb. Sequences displaying the whole history of that deposition are very well exposed at many localities in Jordan. Near Amman eight formations have been recognized. From older to younger these are Rumeimin, Salihi, Suweilih, Naur (these four first formations have, in several studies, been united in the “Naur Limestone”), Fuheis, Hummar, Shueib and Wadi Sir. All together they have traditionally been interpreted to compose the Ajlun Group that is dominated by limestones and marls and is overlain by chalks, flint-rich chalks and limestones and marls of the Belqa Group. Sequence stratigraphical analysis of the Ajlun Group resulted in the recognition of seven sequence boundaries and eight sedimentary sequences which are more or less in agreement with the Cenomanian-Coniacian deposits of the region near Amman with their eight formations.

The formations have here been further subdivided into 37 members which can be recognized and studied in the area of Amman, especially around Rumeimin with regard to the lower predominantly Cenomanian portion and in the area of Wadi Sir for the upper part, predomantly of Turonian to Coniacian age. The formations can be traced from Jerash – Amman region and from here to the south into the area of Wadi Wala, Wadi Mujib and Wadi Karak. They are less well differentiated in the south of Jordan. Especially in the far south in Ras en Naqeb area the five lower formations have collectively been included in “Naur Formation”.

Rumeimin Formation has its type locality near the town of Rumeimin in the eastern flank of the steep Wadi Salihi near the location of an ancient water mill (Fig. 81). Its base is formed by varicoloured fluviatile sandstone of Kurnub Formation with the tracks of dinosaurs (member 1). Their feet had been impressed into the sand in the depression between two wind blown dunes. Rumeimin Formation is about 20 m thick and displays a cycle of the sea coming, remaining and leaving again (transgression and regression). It consists of three members (2-4). The Nodular Limestone Unit includes Rumeimin, Salihi, Suweilih and Naur Formations.

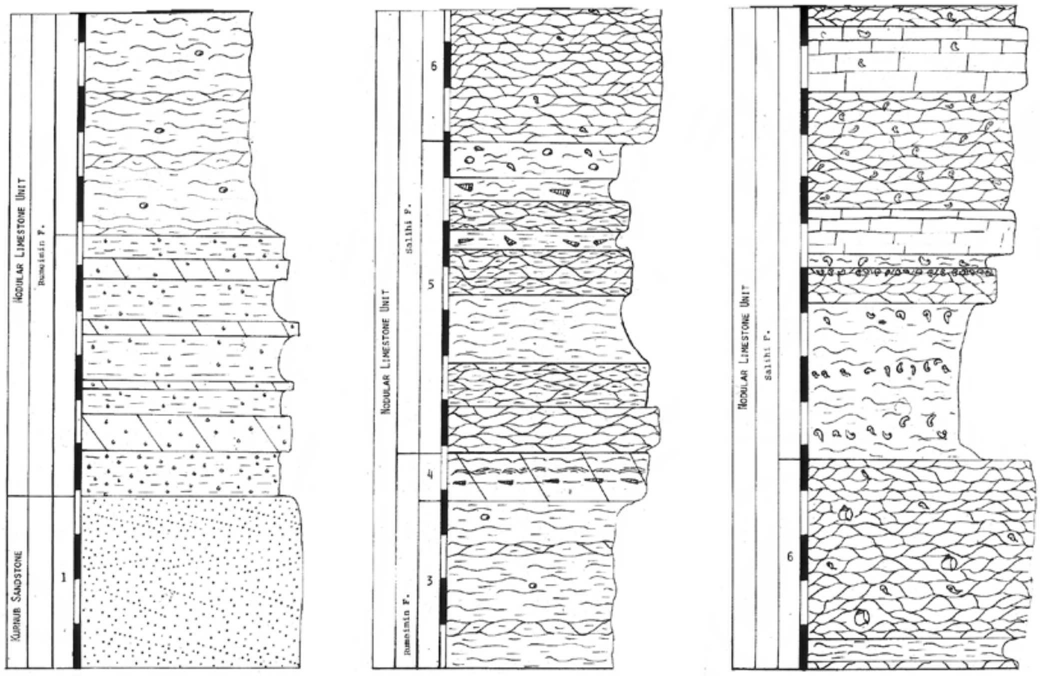

Fig. 81: Scetch of lower part of the Upper Cretaceous section as developed near Rumeimin

Member 2 consists of 6 m of glauconitic marls and limestones. The glaucony and greenish marl is intercalated with dolomitic beds that displays a networks of crustacean burrows and contains oysters of the *Exogyra* type (*Exogyra* and *Rhynchostreon*). Member 3 is about 10 m thick with its marly and nodular limestone beds with oysters but also irregular and regular sea urchins (*Tetragramma* and *Trochotiara*). Crustacean burrow networks are preserved well in the nodular marly limestone with a totally bioturbate background. The fossils present steinkerns of heterodont bivalves and *Tonna*- and *Fusus*-like gastropods. Member 4 measures about 1.5 m and consists of well-bedded dolomitic limestone with intraformational conglomerate at its top. Bedding planes present oriented turriform gastropods, ripple marks, are scoured, have scratch marks and mud cracks. Several beds have stromatolitic structures with some stromatolites up to 5 cm in height and 7 cm in lateral diameter. Gastropod shells are more or less decalcified and in some layers are preserved only as triangular imprints on the bedding plane. Small bivalve and gastropod shells are enriched in some of the ripple valleys. From the mud cracked and sun backed surface layers clast have been transported and concentrated in intraclast layers. Bioturbation here consists of few U-shaped burrows.

Rumeimin Formation displays a number of characters of the sediment which return in the succeeding sequence of Cenomanian–Turonian deposits in Jordan. A distinct feature of this formation is the glaucony of member 2. The green mineral glauconite has been formed in place (authigenic) during the deposition of the sediment and at the time when its particles were still in direct contact with sea-water. Sand-size grains of glauconite develop today on continental margins and on ocean highs, as well in shallow tropical environment, as also on relatively deep bottom but above the slope to the deep ocean. Glauconite is of variable mineralogy and represents authigenic mineral phyllosilicates (clay minerals). Often the cavities of small shells such as bivalves, gastropods or foraminifera are the places in which glauconite clay grows. It is a good indicator mineral for a fully marine origin of the sediment in well oxygenated water. Once formed grains are quite stable to decomposition and can be reworked and transported to secondary deposit, just like other sand sized particles. Their composition allows reconstruction of the time of their formation due to the presence of unstable isotopes in their mineral structure. But resultant age determination have to be carefully evaluated since the chemical composition of glauconite can change during erosion of the mineral and the grains form in secondary deposit which therefore would appear older than what they actually are.

Regular sea urchins, as in member 3, occur throughout the sequence and belong to several genera and different families. Members of the genera *Salenia* of the Saleniidae were recognized from Cenomanian beds. They occurred widely distributed over the shelf area of the Tethys onto the African Continent and are also present in Wadi Qena of SE Egypt. The corona of *Salenia* has two pore pairs in its ambulacral plates, and large spines. There are still living species of this genus. *Heterodiadema* (Hemicidaridae) and *Tetragramma* and *Trocholiara* (Pseudodiademidae) have a low corona with wide and flattened apical side and narrower spines and are found in Cenomanian as well as Turonian beds. *Heterodiadema* is related to *Diadema* that has a common species with long mobile hollow spines in the shallow lagoon of fringing reefs in Aqaba. *Goniopygus* of the Arbaciidae has a hemispherical small corona of about 15 mm wide and 8 mm high and is present in the Cenomanian. Living *Arbacia* prefers solid ground on which it grazes and is often present on the rocky shore. Important stratigraphic indicators are represented by *Phymosoma* and *Rachisoma* of the Phymosomatidae which lived in Late Turonian and even later, indicating that the age of the upper Wadi Sir Formation. The shape of the corona and the characters of the plates composing it are good indicators of the function of the sea urchin. The number of ambulacral feet with which the animal moves is reflected in the number of pores present in the plates of the ambulacral rows. Regular sea urchins rarely move by means of spines but these serve as primary means to defend themselves. They climb and cling to hard substrates with their tube feet which extend through the plates of corona along the pores of the ambulacral plates. Regular sea urchins feed with a powerful internal jaw (called the “Lantern of Aristoteles”) and graze on algae and sedentary organisms. Best for reconstruction of their life is the actualistic comparison with living species, a study that in Jordan can easily be carried out at Aqaba.

The irregular sea-urchins that have lived on the Cretaceous shelf of Jordan differ from regular ones by the heart-like shape of their corona. They had numerous and very short spines and lived within the sediment. When moving in the bottom substrate of the sea during their search for food they transport sand grains from their front along the sides of the body to their rear, bioturbating the substrate in which they live and destroying all of its preexisting structures. The mode of movement of heart-sea-urchins has been studied in detail in case of the living *Echinocardium* from the North Sea which in general resembles the heart urchins found in the Cretaceous of Jordan. It lives up to 20 cm deep in the loose sandy sediment stabilizing its burrow somewhat with mucus. In direction of movement the short spines penetrate the mucus layer and transport grains individually over the body to the back. Ambulacral feet between the spines and arranged in rows select organic particles and transport them to the mouth. Periodically, especially long ambulacra on the top of the corona open a canal to the surface of the sediment to allow fresh water to enter the burrow. The screened sediment left behind by the sea urchin has a distinct and characteristic structure of backfill type. In layers with sea urchins in the Jordanian Cretaceous bioturbation was usually so intense that all individual traces were eradicated, and the calcareous sand, in addition, changed some of its composition later on during diagenesis. But the presence of the heart-urchins in the sediment provides information regarding the composition of that sediment. It consisted of relatively loose sand that contained oxygen rich interstitial - water and was not muddy.

Species of the heart urchins *Hemiaster*, *Mecaster* and the very similar *Jordaniaster* have been characteristic inhabitants of the Tethys during Cenomanian and Turonian times. They differ only little from each other. *Mecaster* has an ovate test with a distinct anterior groove (sulcus) and *Hemiaster* has a weak anterior sulcus and a similar posterior side, and the test a little more inflated. It closely resembles *Jordaniaster*. The tiny spines covering the corona like fur occur very commonly detached from the corona in the limestone. They may also be common in such layers in which the sea urchins have not been preserved. Their presence is indication for that they probably had lived here but their corona has not been preserved as a whole. From modern heart urchins it can be assumed that in order to be preserved with their corona unbroken the animal after its death had to remain in the sediment until at least early diagenesis consolidated the plates of the corona. During this process of calcite crystallization the many different plates of the corona become fused with each other. The fine porous composition of each plate changes into a solid calcite crystal that behaves like a single crystal in polarized light and crystals formed within the individual plates fuse with each other. In case the heart urchin leaves the sediment to die on its surface all organic material decomposes very rapidly. Not only the spines fall off, but also the organic fibers which hold the plates of the corona together disappear. As can be studied with irregular sea urchins that live within the sand in the lagoon at Aqaba, as soon as they are exposed, their corona becomes very delicate, decomposition of the soft parts is very rapid and the corona soon breaks into its individual plates when touched or washed around. To be preserved as is the case in many beds of the Cretaceous of Jordan; the corona had to be surrounded by calcareous sand until the crystals of their skeleton had turned into solid calcite crystals which fused with each other. It is also only after that early process in diagenesis that the corona could become deformed by compaction, as is commonly the case or be washed from the sediment and be settled by oysters, as is also observed in some layers.

Salihi Formation is about 50 m thick and has been subdivided into eight members (5-12). It is well exposed in its type locality, the deep Wadi Salihi which is the first ravine east of the town of Rumeimin. A very conspicuous yellowish massiv limestone of the members 10 and 12 represent a useful marker horizon forming a strong drop off with water fall.

Member 5 consists of 7 m of intercalation of nodular limestone, nodular marl and marly clay. All beds are bioturbated, and layers with moulds of gastropods and bivalves and shells of exogyrid oysters are present (*Amphidonte* and *Rhynchostreon*). In the upper marl irregular seaurchins are common.

Member 6 is about 8 m thick and consists of two beds of hard nodular limestone separated from each other by half a meter of marl. In Wadi Salihi these limestones form a cliff with a high waterfall, and a similar situation is developed in the wadi near Rumeimin and also near Naur to the west of Amman (Fig. 82). Beds are totally bioturbated and hold large fossils such as the steinkerns of *Tonna*-shaped gastropod, sometimes determined as *Strombus* and shells of exogyrid oysters.

Fig. 82: Wadi Salihi with part of Salihi Formation and remains of ruin of an ancient water mill.

Member 7 is a 12 m thick soft marl and a hard nodular limestone above that is bioturbated strongly with a crab-burrow network of the *Ophiomorpha*- and *Thalassinoides*-type produced as last bioturbation deep within the original carbonate mud. Gryphaeid oysters are present throughout, in some layers forming shell beds (Fig. 83).

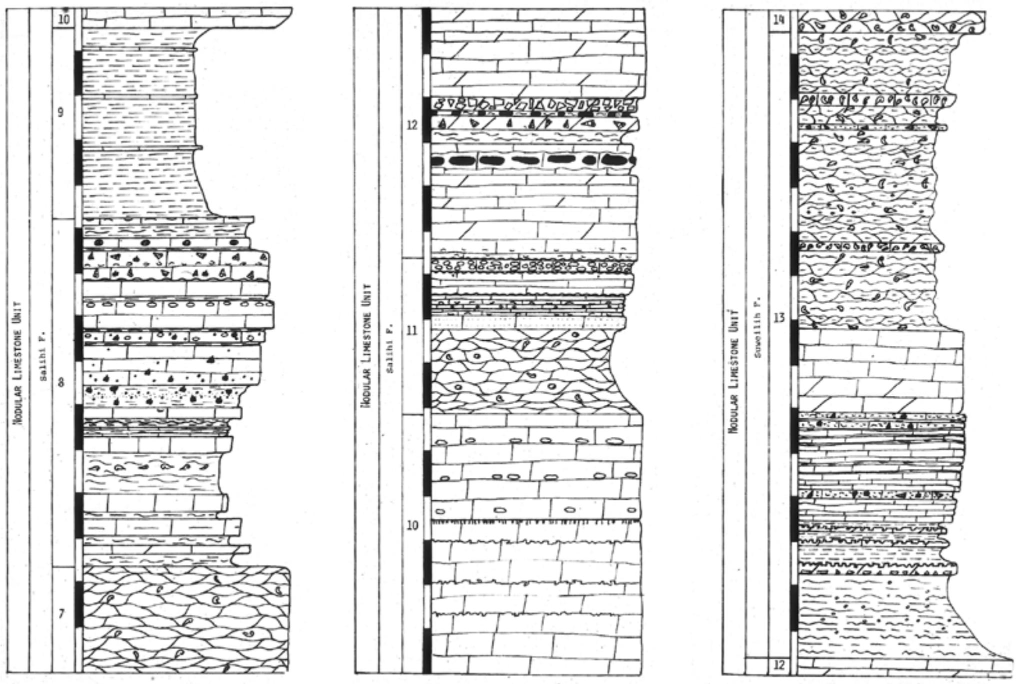

Fig. 83: Sketch of Cretaceous section as developed in Wadis Salihi

Member 8 is about 8 m thick and begins with an intercalation of somewhat bioturbated dolomitic limestones and marls containing small gryphaeids. Quartz, phosphatic and ferruginous sand and small pebbles along with reworked limonitic steinkerns of gastropoda and polished vertebrate teeth and bones are intercalated with clay, marl and limestone beds in the central portion of the member. Large U-shaped burrows with up to 1 cm wide tunnels are present. The overlying limestone is intercalated with clay and sandy silt containig crab burrows. Layers composed of intraclasts as well as conglomerates of small quartz pebble and layers of clay pebbles are present, and bedding planes may be rippled with gastropods and bivalves enriched between crests. An upper limestone bed is riddled by up to 10 cm large round holes isfound filled by coarse cement-calcite.

Member 9 consists of clay beds of about 4 m thickness with several thin limestone beds with rippled surface (crest distance 1-2 cm), desiccation cracks and some trace fossils of *Planolites*-type, representing fecal pellet-filled burrows of 0.8 to 1.0 cm width, are intercalated into the greenish and grey clays. During deposition of member 8 the sediment was periodically exposed to the atmophere. Member 10 is a 6 m thick laminated limestone that forms a prominent cliff in Wadi Salihi. Burrow structures did not destroy the original sediment structure. Some bedding planes were dolomitized and became bored by bivalves with their pear-shaped bore holes filled with yellow clay which also forms interlayers of clay.

Member 11 consists of nodular limestones 3 m thick with rich marine fauna consisting of gryphaeid oysters, gastropods, irregular and regular seaurchins at the base. The limestone above contains quartz sand and is overlain by thin bedded limestones with numerous small bivalves of which most have both valves still articulated. The uppermost beds have ripple surfaces and a layer composed of mud balls above. Member 12 is 6 m thick and consists of laminated and, in parts, dolomitic limestone beds. Two layers contain flint nodules. Limestone intraclasts (rip-up structures) formed on and of a lithified bed that is intensely bored by endolithic organisms. Only a few bivalve and gastropod shells are present and little bioturbation developed. This documents that with the end deposition of Salihi Formation the ground fell dry again.

During the deposition of Salihi Formation the sea flooded, remained some time, and retreated from the type area several times. The structure and composition of the sediments reflects the periods when the ground fell dry repeatedly.

Among marine Gastropoda, as noted in member 6, by mid Cretaceous time, Latrogastropoda evolved which resulted in the appearance of relatives of most of the conspicuous species which now hunt prey in the sea. Among those evolving *Fusus*-like forms with elongate siphon canal appear, but they can be confused with *Aporrhais* and *Strombus*-like forms which were present long before the evolution of Neogastropoda (part of Latrogastropoda), at the begin of the Jurassic. Stromboidea live quite differently from these feeding on algae. Most Latrogastropoda are carnivorous animal which usually hunt a specific prey. Their preservation in Cenomanian and Turonian rocks is not good and not sufficient to determin them to the species, genus, often not even to a larger taxonomic unit, because they usually have an aragonitic shell. It was usually dissolved even before compaction of the sediment could deform them further. Only very large shells have survived long enough that their internal filling consolidated by cementation to such a degree that they retained their shape. A determination of species is no longer possible and also the generic place can only be assumed from general morphology. But since many convergent shapes had evolved in quite different relationships a determination may be quite misleading.

Aragonitic shells as well as all aragonitic particles in the carbonate sediments were dissolved during the process of limestone formation from the loose bottom substrate. This dissolution occurred relatively early during rock formation (diagenesis). Small and thin shells dissolved earlier than thick and large shells. The internal cavity of larger shells was commonly filled with sediment, that when the entrance to the cavity was small was often of finer grain-size than that of the surrounding material. Such selection of fine material to fill the interior can be observed where the entrance into the interior of the shell is small, for example through the narrow gap of a bivalve or the thin siphonal canal connecting the chambers of an ammonite. Carbonate mud suspended in the water that entered by that way settled in the slack environment of the interior cavity of the shell. Thus fine-grained material within the shell was during diagenesis often cemented more rapidly than the coarser and less sorted material surrounding the shell. So when the outer shell layer was finally dissolved the internal fill had its own preservation potential. Often it was still plastic and culd become deformed during final sediment compaction, but it could also react like a stone and was no further defomed. When the internal fill was still plastic the cavity of the dissolved shell may have closed and ornamental features that lay on the outside of the shell could have become imprinted onto the inner filling. This way a steinkern acquired the pattern of ornament of the outer shell, as is commonly encountered in these sediments. And last not least, consolidated internal fills could have been washed from the sediment when currents eroded it and concentrated in pebble layers in the internal fill of a bivalve, gastropod or cephalopod. In case these were still plastic they were preserved only in their general shape as the gastropods in member 8.

Mud cracks can form only when a fine grained substrate, in this case carbonate mud, lay dry and is baked by the sun. Usually the surface of the wet or moist sediment has was settled by cyanobacteria and when conditions for animals feeding on them became bad as is the case under saline conditions they form a dense mat that hardened the surface when it dried. When water returned these dried mud sherds can be picked up by the current and be relocated into layers of such sherds, which are characterized by angular outline and may have upturned margins. Such a deposit thus represents good evidence for the former presence of a sun backed intertidal or supratidal surface. When sherds are washed further they may become rounded, forming mud balls. But similar deposits of mud pebbles can also form when the sea erodes surface sediment down to a level in which consolidated layers are reached and become eroded. The deposit thus formed may be called an “intraformational conglomerate”. Carbonate muds exposed to the sun may also be cemented. Very rapidly this can occur by salt forming the cement, and in case the salt is gypsum it will not readily be dissolved again when the surface crust becomes reworked by the sea. Muddy lagoonal bottoms that have fallen dry for a longer time and on which during rainy periods fresh water puddles formed with fresh water entering the pore space are consolidated by carbonate cement. In a climate as is now present along the shores of the Red Sea surface layers are cemented under that condition by aragonitic or calcitic cement. When such surfaces are eroded the angular fragments can be washed together forming breccia which may represent “rip-off structure”. A differentiation of the different modes of formation in the rocks as for example in member 12 is no longer possible since the fragments have since changed their composition by the following diagenesis of the limestone bed to its present state. Such deposits are indicators for exposed marine carbonate bottoms under the influence of the air, salty water and sun for an extended time and later became flooded again.

The conservation of ripple surfaces is an indication for currents strong enough to carry sand grains. Mud balls document that consolidated mud was eroded to form fragments which were transported and on their way became rounded, and when bivalves were washed from their home in the soft bottom and deposited. Here they became burried and died in that place, since they had their ligament still holding the valves together. In case they had the chance to decompose, this organic ligament was eaten by fungi and bacteria and valves detached from each other. Oysters growing only to juvenile stage are also indicative for an environment that was not stable enough to allow their life to contiue after initial settlement as may be the case in a shallow water body of intertidal area. With member 7 up to 11, such a shallow water environment is documented, ending in dolomitc beds (shallowing up succession).

When a carbonate surface lies exposed for an elongated time it may become consolidated by minerals growing in the pores space. Such surfaces represent the environment for a number of bivalves to have their home. Several evolved during the Jurassic and are able to bore holes into limestone. For doing so, they use their foot, the margin of their shell and the so called extrapallial liquid. The later represents a mucus that is secreted by the mantle tissue that underlies the shell. The mucus can dissolve Calcium-Carbonate, the foot can spread it onto the surface that needs to be bored and the shell edge can detach loose particles. *Lithophaga* among the Mytiloidea, *Petricola* among the Veneroidea are such bivalves. Their bore holes have a characteristic club-like shape and where such holes are found in a bedding surface, they represent evidence for a hard ground that was submerged in the sea at least periodically at every high tide (member 10).

Suweilih Formation with members 13-18 is about 70 m thick and recognized (in Wadi Salihi and the area of Suweilih at the southern margin of the Baqaa depression in northern Amman) as shallow water deposits succeeded by fully marine deposits and ending with deposits of lagoons and shores.

Member 13 measures about 7 m and consists of basal clay and marl, and central marl and limestone. Here the surfaces form hard ground that became bored. Beds contain layers with mud-cracked surfaces. Other beds consist of reworked fills of small gastropods that have lost their shell, fish bones, teeth and ostracods and also glauconite and quartz sand. A top layer is formed by beds of laminated and dolomitic limestones with single U-shaped burrows of 2-3 cm wide tunnels.

Member 14 consists of 20 m of totally bioturbated nodular limestone and marl with nodules that have diameters of about 10 cm (Fig. 84). Here gryphaeid oysters predominate and shell coquinas are present. Macroforaminifera (orbitulinids) occur commonly near the base of the member. A thin bed with ostracods, small gastropods and fish teeth follows. Some beds of the following sequence contain numerous steinkerns of bivalves and gastropods, others calcitic worm tubes and pectinid shells. Some beds have regular and irregular seaurchins, and others ammonites. Member 15 is about 15 to 20 m thick with totally bioturbated clay and marl containing gryphaeid oysters in the more calcareous beds and plicatulids in clay-dominated beds. Member 16 consists of 3 m of massive grey and totally bioturbated marly, soft limestone containing large bivalves in living position. At Rumeimin, solitary corals as well as smooth shells of pectinids and few gryphaeids are also present.

Member 17 in Wadi Salihi consists of 10 m of limestone which forms prominent cliff producing small waterfalls. The lower beds contain many molluscan fossils, mainly large gastropods and regular seaurchins. A layer of flat, large oysters has the shells infested by many endolithic organisms. The bulk of the member consists of white nodular limestone with *Nerinea* and related gastropods, *Actaeonella,* a rudist bivalve and a conspicuous network of *Ophiomorpha-Thalassinoides*-like burrows. Near Iraq al Amir to the West of Amman rudists are common.

Member 18 with 7 m in thickness. Its lower portion is an intercalation of *Nerinea* limestone and gryphaeid oyster marl. Actaeonellid gastropods are common in several beds, and the patelloid neritacean *Pileolus* has settled on a hardground surface. The upper part of the member consists of birds-eye limestones with hardgrounds on some bedding planes.

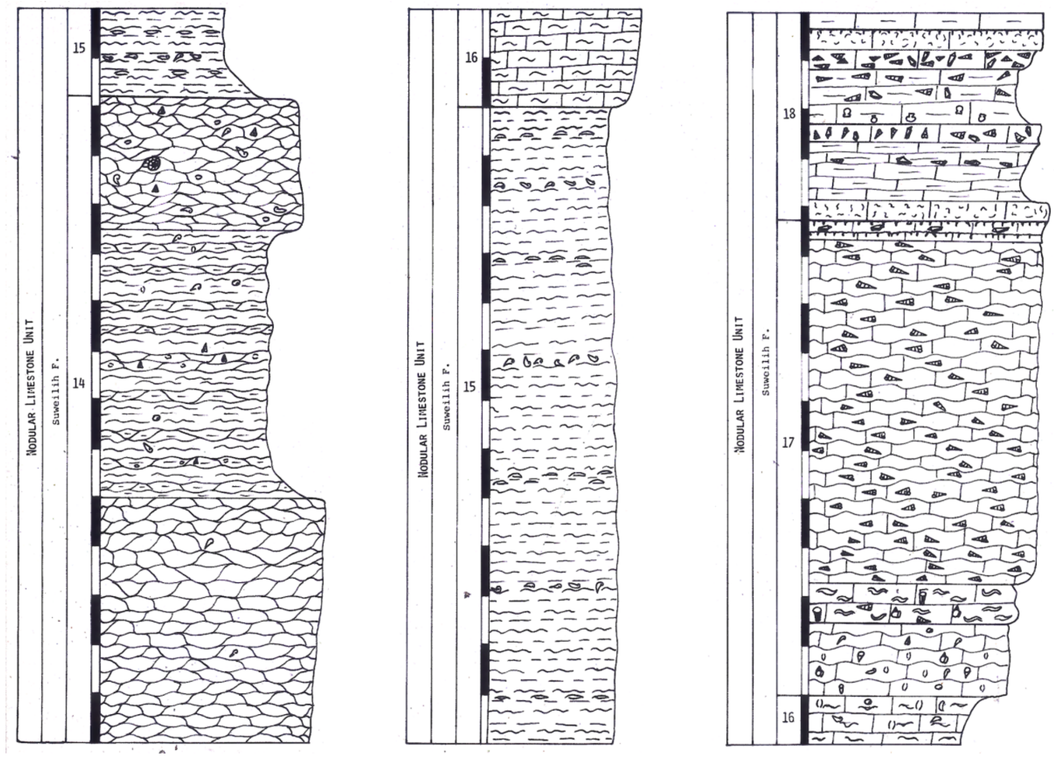

Fig. 84: Sketch of section as developed in Wadi Salihi.

Deposition of Suweilih Formation began in a coastal environment with initially reworked glauconitic sand and quartz sand indicating a longer period of omission. Later in shallow water with illuminated sea ground.Than in open marine environment with many bivalves, even corals, and later more in protected lagoonal environment with the characteristic gastropods of that environment and ending with beach rock and mud as a surface to cyanobacterial crust, as formed in peritidal environment.

Winnowing of sediment after it was deposited and before it turned into rock washes small and light particles away leaving larger and heavier particles behind. That way materials that formed in the sediment, can be concentrated such as grains of glaucony, and internal fills formed within shell space. In layers formed under oxygen depleated conditions small gastropods or bivalves could be filled by pyrite that may crystallize in cavities when the pore water is rich in H2S. When eroded from the sediment these heavy ironsulfides will oxidize and transform into ironoxide. Also phosphate particles such as teeth and bones become exposed. In such cases, where quartz sand or even small quartz pebbles are present, several sources can be reconstructed. Quartz was carried on the holfasts of algae which was washed here during storms from far away shores. Quartz pebbles could have been carried in the stomachs or marine reptiles, or they have been washed here during heavy weather from far away, known southern and unknown eastern shores. In the area around Amman there was definitely no source from which quartz sand and pebbles could be picked up during Cenomanian and Turonian times. The shore during these times lay far in the east and southeast of Jordan and the shelf region covering the northern portion of of Gondwana lay on a flat plane.

Large foramininfers as in member 14 belong to the alveolinids. *Praealveolina* represent spindle-shaped, cigar-like large foraminifers which are interpreted as related to *Alveolina* from the Paleogene which have similar forms among modern large foraminfera from the tropical Pacific Ocean. These latter live in symbiosis with unicellular green algae and thus occur only in well illuminated shallow water. The growth of large foraminifer occurs bythe addition of one tubular chamber parallel to the axis of the shell, with perporate walls to the next chamber and perforated walls across the chamber. The walls between successive chambers piled on top of each other in the coil are continuous. Thus the shell appears cellular in section. These large *Praealveolina* and related species (*Ovalveolina*, *Orbitolina)* are thus indicative of shallow tropical sea water. Somes species are characteristic to the time in which they lived and thus repesent good biostratigraphic indicators.

Some sponges among the Demospongia etch their home into calcareous substrates as in the oyster shell of member 17 and such activity can be noted to occur commonly since the Jurassic. The boring sponge preferably settles shells of larger invertebrates such as mollusks and corals which have their shell surface exposed to seawater for an extended time. *Cliona* among the Clionidae etches holes into carbonate which are arranged like strings of pearls connected to each other by narrow canals. By this boring activity solid shells are considerably weakened in their structure and can subsequently be destroyed rapidly to form carbonate sand.

Nerinea represents a characteristic lagoonal gastropod which has lived through Jurassic and Cretaceous and disappeared afterwards. Its occurrence in Cretaceous deposits in Jordan is usually a good indicator for deposition in lagonal or near lagoonal environment. The characteristic features of the shell of *Nerinea* are folds present not only on the columella (spindle) but also on the inside of the outer lip. These folds continue on the inner side of their whorls and can usually be traced back to the smaller whorls that were formed during earlier stages of life. The functions of the folds during the life of the gastropod are unknown, but they help in the determination of the species since they are also seen well when the shell has become part of solid limestone as is the case in Member 16 or when the shell is only preserved as cast or internal mold as is the case in the Rabad rudist bank at Istefena in Ajlun. Nerineids occur in lagoonal limestones as in Members 17 and 18 in great numbers. Here species of *Diozoptyxis* and *Ptygmatis* have grown to large size, so that their food must have been different from that of the modern pyramidellids with similar shell shape, which suck blood of hosts. *Diozoptyxis* grew to 7 cm in length *Ptygmatis* even to 35 cm. Their conical shell consists of many (more than 15) angular whorls. *Trochalia* in contrast has more rounded whorls and smaller shell, less than 2 cm in length. Its columella is hollow and general shell shape more spindle like. *Diozoptyxis* and *Trochalia* are common in the lagonal limestone of Suweilih Formation and are present in other localities as for example Wadi Hisban. Similar gastropods often determined as *Nerinea* are known from Cenomanian deposits of Israel and Lebanon. The only gastropod group with similar, but usually much smaller shell with size of approximately 1-5 mm are nowadays the Pyramidellidae. They are parasites on other molluscs and worms and have a large number of species many of them living in the Gulf of Aqaba. Convergent shell shape, at least regarding size, external shape and composition of the wall is found in case of *Terebra* that lives in the Red Sea and feeds on worms. But the allogastropod *Nerinea* and the neogastropod *Terebra* are not related to each other, but perhaps worms represented their food.

Pileolus was a limpet-like gastropod that grazed algal crusts from beach-rock surfaces. It is a member of the same group of gastropods as the modern *Nerita*, which is common on the beach of Aqaba. Both have a special character that all internal walls of the shell are dissolved, as is the case in most members of the Neritoidea since Triassic time. But *Pileolus* (*Salihia*) lived differently, more in a lagoonal environment grazing algae from hard surfaces of beach rock (Member 18). The shell has a thin calcitic outer layer, as is the case among this group of gastropods in general to which also the modern *Theodoxus* belongs, common in clean fresh water in Jordan. But *Pileolus* lived in the sea and the genus is known only from Jurassic to the end of Cretaceous. The Jordanian subgenus *Salihia* is special among them since it is rather large (more than 3 cm high and wide) and has strong ornament of radial ribs. Today *Septaria* represents a convergent limpet-like member of the same subclass Neritimorpha that also has species in lagoonal environment, living in the tropical Indo-Pacific. But the evolution of that group began just after *Pileolus* and the closer relatives among the Neritimorpha were extinct.

Birds- eye- limestone, as in the base and top layers of member 18, is a characteristic facies which developed from fine grained muds of the lagoon. When these are strongly illuminated in shallow water cyanobacteria grow on the surface of the mud and produce a dense layer within which oxygen bubbles form. These can not be released and remain as cavities within the mat when it calcifies. Other bubbles below the growing mat may also form when the organic material produced by it is decomposed by bacteria, and in that case CO2 bubbles could form which may also not be released to the sediment surface and remain as cavities. Later during diagenesis the cavities are filled with calcite forming the “birds-eyes” in the fine-grained lagoonal limestone.

Naur Formation as developed in the Amman region has its type locality at Naur to the west of Amman. It measures about 50 m in thickness and holds member 19-22. Here deposits of the open shallow sea predominate, sometimes having lagoonal appearance. The upper part of the sequence was deposited in an environment with little influence of silico-clastic clay suspensions. The sequence ended with early diagenesis under the influence of saline water with transformation into dolomite.

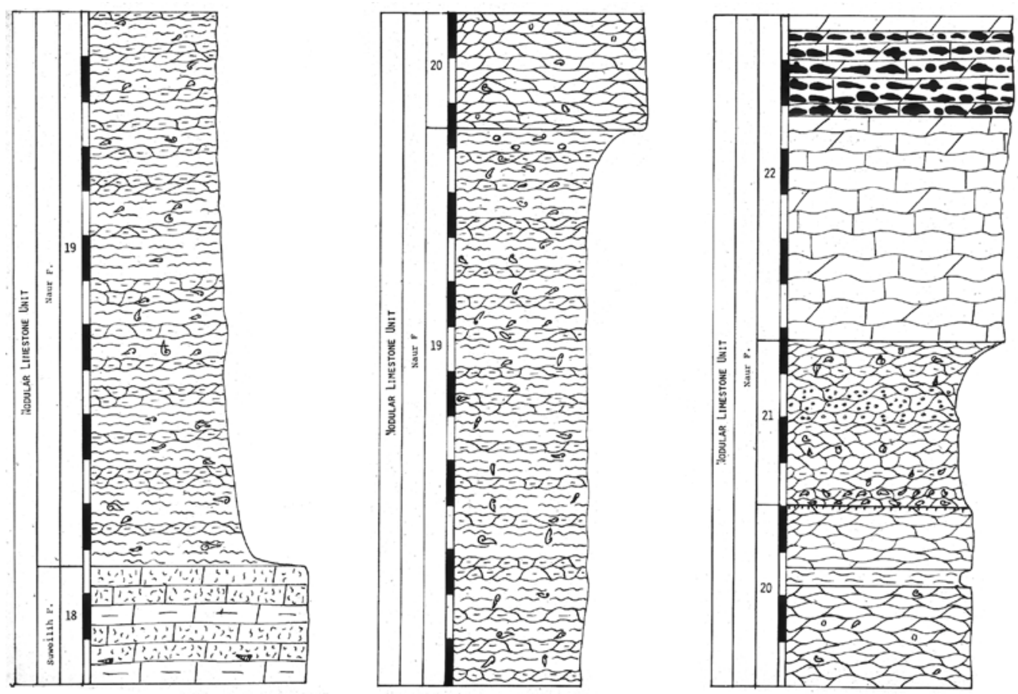

Fig. 85: Sketch of section of members 19-22 as developed in Wadi Salihi

Member 19 consists of about 25 m of bioturbated marl and nodular marly limestone, chalky in part. It contains gryphaeid and exogyrid oysters mixed throughout. *Ophiomorpha* and *Thalassinoides*-like burrow systems are part of bioturbation. The uppermost bed contains irregular seaurchins.

Member 20 is a thick, pure-fine-grained limestone with stylolite sutures in the lower part. It is separated from the nodular limestones by bioturbated marl. The member in Wadi Salihi is 6.5 m thick (Fig 85). At the northern end of the Baqa'a depression the limestone holds many corals, rudists, nerineans and seaurchins. Crab burrows in the upper portion of the member are compacted to half their height. The upper surface is formed by a hardground, pierced by burrows which are filled with sediments of the layer (member 21) above.

Member 21 consists of 4 m of very fossiliferous nodular limestone and marly shell beds of gryphaeid oysters. Also present are many bivalves such as relatives of *Pinna*, exogyrids, pectinids, and arcids along with gastropods of the nerineid, naticid, and stromboid type and irregular and regular seaurchins. In layers many orbitolinid macro-foraminifers occur.

Member 22 consists of 13 m of dolomitic, massive nodular to banked limestone which in its lower portion contains well preserved *Ophiomorpha* burrow systems. The central portion has 6 layers of flint consisting of up to 7 cm thick flat nodules. The upper beds are strongly dolomitized.

The amount of silicoclastic clay that may be mixed with the calcareous material in the sediment has a great influence on the appearance of the rock formed from these deposits during the processes of diagenesis. In case of practically no clay, the lime sand-mud mixture changes its composition in the disappearance of aragonitic particles either before or after cementation. Whether one or the other was the case can be checked by preparing thin-sections of the rock. When tiny shells of gastropods or bivalves are recognized, cementation must have occurred before aragonite dissolution. In case aragonite is dissolved when the sediment was still plastic, later compaction will eradicate the traces left by dissolved shells. In that case no shells of originally aragonitc composition remain and the only tiny shells preserved are those of former calcitic or phosphatic composition. Foraminifers are often small and usually calcitic, therefore they often survive this process. The sediment turns into limestone by closure of all pore spaces with cement. In the case when pressure on the limestone increases due to overload or structural compression, the last water contained between crystals begins to migrate along fissures which form vertical to the strain. Thus styolithe sutures appear which have a dented appearance and on which material, that cannot be dissolved, is enriched. Stylolithe sutures only form in quite pure limestones.

In case, lime particles are mixed with silicoclastic clay a more or less strong concentration of either material will proceed during rock formation. The bottom substrate is usually well mixed due to the activity of the fauna that lives in it (endobenthos). The repeated transition of the sediment as a whole or as single particles through digestive systems for example of sea-urchins, holothurians and all kinds of worms corrode particles and break them down in size. Larger skeletal remains are settled by boring organisms such as boring sponges, bivalves and others forming larger holes or by boring micro-organisms such as fungi, algae or bacteria. Therefore, they are repeatedly usefull as food to substrate feeding organisms. The boring activity of microorganisms leave their traces by forming fine grained (micritic) rims in the surface of skeletal elements of all sizes down to that of sand grains. The passage of the sediment through diverse digestive systems is also quite evident in such localities where cementation was relatively rapid and preserved the original structure of the sediment. Such limestone displays in the thin-section a pelletoidal composition.

Mixing materials and breaking down their size continue until the sediment is burried so deep that normal endobenthic organisms such as worms, sea urchins, bivalves etc. no further reach it. But still these regions in the sediment can be supplied with fresh water from the surface by crabs which construct their homes to reach down for, sometime, more than one meter below surface (Fig. 86). So bacterial decomposition of organic material can go on. Where much organic material is still present the chemistry will change to anaerobic and this may change the composition of the pore water. Circulating pore water eventually dissolves CaCO3 locally and redeposit it again, locally as cement. In places, crystals of the cement initially forming crystal growth attract further growth so that locally CaCO3 is enriched. At the same time locally clay becomes more concentrated due to the migration of the lime to cementation spots. This migration within the forming nodular limestone does not particularly follow burrow structures. It ends when the lime-richer parts are solid due to cement formation and the clay richer parts have very little carbonate left in them. During compaction more water is pressed out and clay richer beds aquire a laminated structure. Due to that late shifting of cemented portions against clay-rich more compacted portions the limestone increases its appearance of undulating nodular structure. In case that more clay is present in the original sea bottom this separation goes even further with the result of undulating limestone beds intercalated by irregularly laminated claystone.

Fig. 86: Horizontal network of the basal part of crab burrows

Single corals of the *Fungia* type which are smaller than modern *Fungia* determined as *Aspidiscus* or *Cyclolithes* are sometimes preserved. They may have originally been more common since their skelton was aragonitic. Their life resembled that of modern *Fungia*,found on sand next to the reef at Aqaba. The flat base of the coral lies on the soft substrate and the animal can keep its place on the bottom by using its tentacles to keep away sand, to uncover themselves when substrate is deposited on them after a storm or when they are turned over by a fish searching for food. *Aspidiscus* forms a cupola disc-like skeleton with compact septa which are laterally strongly granulated.

Flint as in the lower member 22 consists of quartz and has formed as opal-like hydrosilicate during diagnesis of the limestone. Its mode of formation is still a riddle and it is also not evident why it formed where it formed. The source of silica is biogenic opal as used by benthic sponges or by planktonic silicoflagellate, diatoms or radiolarians. All these lived in the Jordanian shelf sea at that time but are usually not found preserved in the sediment. Their skeletal elements dissolved in the carbonate sand and were transported by pore water until at a certain spot flint began to grow, for no known reason. At its locality of growth the silica usually replaced and destroyed other sedimentary structures, sometimes with the exception of crystallized large spines of sea urchins. It may occur that flint formed in or near a former crab burrow, but it can not be stated that crab burrows or other burrow structures are the preferred location for chert formation. It is also not evident why flint pebbles commonly grew at a certain level in the rock column, as they usually do.

Dolomitization of calcareous sand and mud can occur under the influence of saline pore water early during diagnesis. Dolomite as a mineral may form only under special conditions as occurring in some saline lakes on land, but not observed in connection to sea water, even not in saline lagoonal bodies connected to the sea. When pore water is saline and circulates within the sediment, transformation of calcite into dolomite commonly occurr. During that process calcium ions are exchanged by magnesium ions until about 30% are replaced. Animals producing dolomite as skeletal material occur only exceptionally. Thus sea urchins usually use calcite as constructing material of their skeletal part, but the anterior parts of their teeth are dolomitic. This is a smart invention since dolomite is harder than calcite or aragonite and thus these teeth can scrape calcareous surfaces without being eroded themselves. In rock sequences the occurrence of dolomite is an indicator of saline water acting on deposited lime sand and mud. This influence can also be applied later to the history of the limestone so that dolomitization can occur through percolating water from other sources than the sea. This has to be taken into consideration when a dolomitic limestone is evaluated.

Fuheis Formation is about 50 m thick and the ammonites document that is may be of late Cenomanian at its type locality. Members 23 to 24 are predominantly deposits of the open sea but erosion of former beds occurred by evidence of layers with reworked and concentrated fossils. (Echinoidal Limestone includes Fuheis, Humar ans Shueib Formations).

Member 23 consists of 23 m of marls intercalated with thin beds of nodular marly limestones, bioturbated throughout and at its base rich in fossils, among them many gryphaeid oysters and regular and irregular seaurchins (Fig. 87). Distinct layers contain well preserved *Pinna* and *Pteria*-like bivalves with both valves still connected. Others have worm tubes and oysters-encrusted ammonites. Still others hold many reworked ammonite steinkerns and casts and steinkerns of bivalves and gastropods in addition to a few nautilids and bryozoans.

Member 24 consists of about 27 m of quite uniform, bioturbated nodular marly limestone. All beds are quite rich in fossils, but preservation is usually that of casts or steinkerns, and only oysters are well preserved. They form a marly shell bed in the central portion of the member. Some layers contain ammonites.

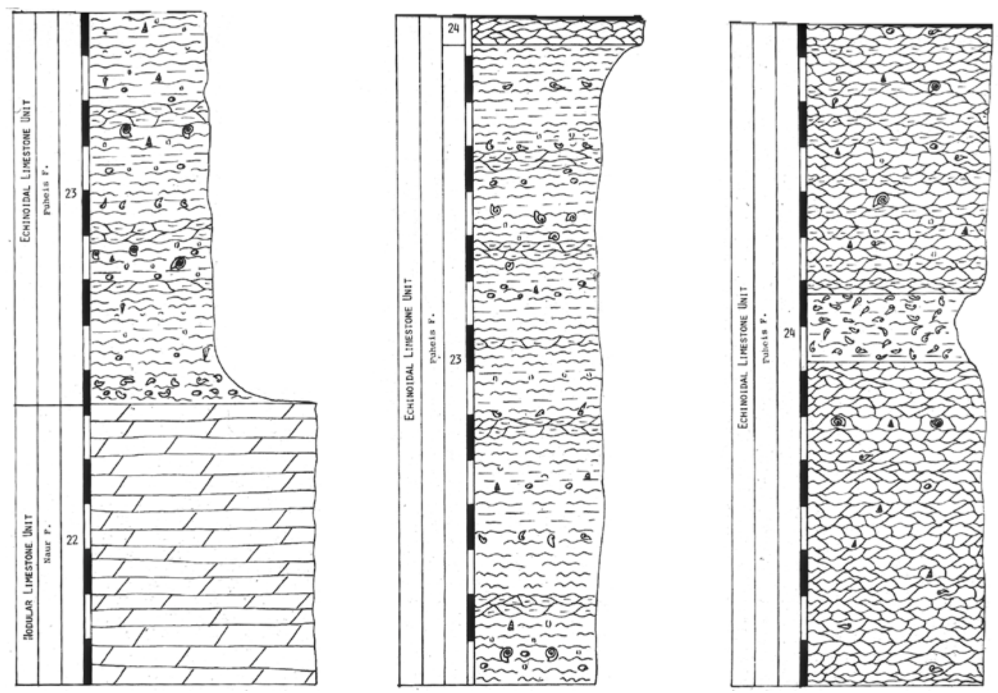

Fig. 87: Sketch of section of memberes 23 to 26 as developed in Um ad Dananir

Pinna represents a characteristic often large bivalve with elongate triangular shell shape. It is usally anchored in the sediment by a bundle of byssus threads and the shell gapes where it extends into the sea water. Often the two valves, in grown individuals, are connected by shell layers and valves can no longer be detached from each other without breaking. Very similar species of the group are known since the Carboniferous and had obviously lived in the same way as can be still observed in the Gulf of Aqaba where *Pinna* and the related *Atrina* occur achored by byssus in the loose sediment of the shallow lagoon. Usually only the upper margin of the shell extends above the ground and most of it is covered by sand. The shell consists of an outer layer composed of large calcitic prisms which may detach from each other and can be found and recognized as single individuals in limestone, with aragonitic inner layer nacre usually disappearing during diagenesis.

Pteria is a characteristic representative of the bivalve group Pteriomorpha with similar species occuring since Ordovician and still present in the Gulf of Aqaba. The shell has a somewhat triangular shape with the margin of the straight hinge expanded to lateral wings, with one wing (anterior shell portion) smaller and the other (posterior near anus) larger. On the side of the foot the shell margins do not perfectly close forming a gap for the byssus threads which attach the bivalve to the substrate. *Phelopteria* represents a genus that lived in the area during Cenomanian. A well known representative of this group of bivalves is the perl oyster (*Pinctada*) which also occurs in the Red Sea and is the producers of perls. Often *Pteria*-like species live attached to octocorals or similar colonial organisms which extend above the sediment surface.

The shells of oysters are usually well preserved due to their original calcitic structure. They are monomyarian which means that their valves are pulled to close with one large muscle. Oysters join the two valves with the elastic ligament attached along the hinge which is straight and triangular in case of the *Ostrea* relation (Liostraeidae = Ostreidae) and triangular and curved in the *Gryphaea* relation (Exogyridae). The left valve is the larger and is attached, at least in the early stage of their life, and the right valve is smaller and lid-like. When grown to larger size the oyster may lie individually on the substrate, but oysters may also be attached to each other throughout life, sometimes even forming reefs that way. Coiled oysters of the Gryphaeidae such as *Amphidonte* have a curved umbo and strong fold-like ribs, *Pycnodonte* with solid shell have their ornament predominantly of growth increments and both occur also in the lower formations. *Rhynchostreon* with the umbo coiled and almost smooth shell and *Laevigyra* with similar shape and fine radial ribs appear with the Fuheis Formation. During Turonian *Exogyra* with lamellar growth increments and *Ilmatogyra* with similar shape and ornament but less coiled umbo are added. All are members of the Exogyrinae which became extinct with late Maastrichtian. *Curvostrea* belongs to the Ostreidae which nowadays is the group representing most living oysters and differs from the other oysters by having the umbo not coiled but only oriented to the side. *Plicatula* is distantly related to oysters and forms beds in Jordan, apparently at locations with muddier bottom, perhaps representing former thicket of large algae to which they might have been attached with their byssus.

Bryozoa represent a group of invertebrates in which many small individuals surrounded by a box like calcitic shell compose together a colony that may be of quite different shape. Some are branched twig-like, others more columnar and others again form crusts on hard substrates. The animals within a colony are interconnected and most are feeding, and some may serve as specialists for reproduction. Bryozoa feed using ciliated tentacles which they stretch out from their shell and can also retract them into the shelter of the shell, often even closing the aperture with a lid. Food is filtered from seawater and consists of predomiantly of phytoplankon (algal cells). While in the Maastrichtian of Middle Europe for example, bryozoa might have been locally so common that they have been the main component of rocks, in the Late Cretaceous of Jordan they occur rarely as in member 23. Nowadays, bryozoa may be quite common in shelf regions and here they may be the predominant producer of sediments, obviously not so on the Jordanian shelf during the Cretaceous.

Hummar Formation consists of members 25 to 27 and measures about 45 m in thickness near Baqaa. Oolites document formation in shallow water. The massive beds in its upper part may have formed in a special way. Similar beds are much thicker at Wadi Hisban and of great thickness and uniformity in Wadi Wala. They were deposited very rapidly from highly turbulent water and differ from most other beds by not being bioturbated.

Member 25 consists of about 14 m of limestones and is well exposed in the valley below the conspicuous fold at Um ed Dananir, at the western margin of Baqqa depresssion (Figs. 88 and 89). Bioturbated marine chalky and marly limestones form the basal beds with dense networks of burrows of the *Ophiomorpha*-type with 3-8 mm wide tunnels in basal beds and fewer ones further up. These burrows are not compacted and are filled with yellowish material that contrasts the white matrix. Nodular limestone may be totally churned by bioturbation with intercalations of marls and limestones. In the upper portion of the member two beds of oolites are developed, separated from each other by well bedded marl. Up to 1.5 cm wide burrows from the oolite extend for up to 70 cm in depth into the marl below and are filled with ooides and not compacted. The final limestone contains layers with desiccation cracks, with intraclasts, or with shallowly undulating stromatolites. Some end in hardgrounds with 1 mm wide calcite-filled tunnels and some are dolomitized.

Member 26 is 12 m thick and consists of two massive yellowish limestone beds separated from each other by a stromatolitic bed. The massive limestone units are indistinctly horizontally laminated and have an undulating surface with a crest height of about 10 cm and crest distance of about 30 cm. Included in the upper bed are 1-15 cm wide round cavities distributed irregularly which may have been pebbles composed of gypsum. The nodular limestones above contain shell debris. The last somewhat dolomitic beds end with bored omission surfaces. The two similar limestone beds, separated from each other by platy limestone near Um ed Dananir, form a waterfall connected to the remains of an ancient ruined mill.

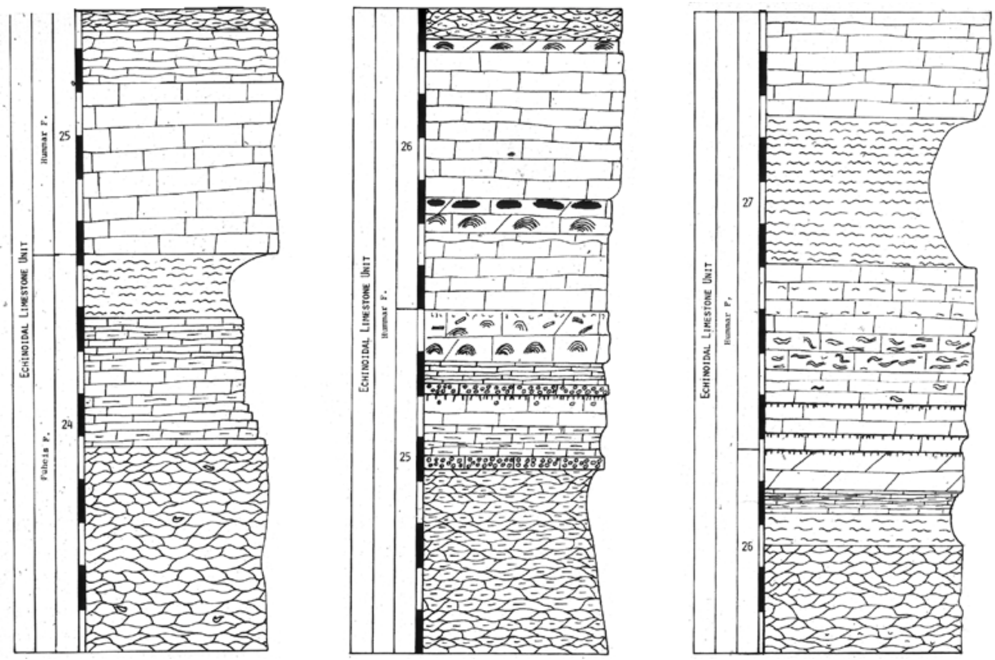

Fig. 88: Sketch of section of members 24 to 27 as developed in the margins of Baqa'a Depression

Member 27 is 19 m thick and begins with chalk penetrated by *Ophiomorpha*-like crab burrows with entrance at dolomitized hardgrounds, extending down for about 70 cm, filled with yellowish dolomitic sand. Following beds are mainly composed of flat oyster shells quite similar to those composing the base of member 17. Both valves are found still connected with each other and they compose a distinct bank. A similar bed composed of oysters also with both valves in place follows above. A bioturbated nodular limestone is covered by a massive yellowish limestone of about 10 m in thickness without indistinct structure and with spherical cavities.

Ooids are coated grains and their formation is well known from moderne environments. Theu were first studied in detail from the Bahama Banks in the tropical Atlantic. In Jordan they can be studied as well from the Cambrian limestones. Along the coast of the Gulf of Aqaba there are nowadays no shallow tidal regimes with shifting sand grains necessary for their development. Ooids form on sand bars and shoals in shallow tropical water. They consist of a core with thin smooth coats of calcite in concentric arrangment around it. Most probably cyanobacteria are involved in the crust forming process. Occurrence of oolites in the rock composed predominantly of ooids indicated formation in shallow turbulent clear, warm water in the very shallow sea. Coated grains may also be noted in environments without sand banks, and here they form quite differently. They can be distinguished from ooids by having a less smooth coat, no concentric lamellar structure but only an even micritic rim as a fine grained crust around a core. Coated grains form due to endolithic boring microrganisms which had settled the grain usually in the illuminated zone of the shallow sea. They might form the core of an ooid.

Fig. 89: Exposure at Um ed Dananir with the members 25-27 in the valley to the left of member 31-33 at the right side with the Cenomanian Turonian boundary in the area of the trees in the center.

Member 25, 26 and especially 27 have massive beds which differ from other beds by having no bioturbation. Instead they preserve an indistinct laminar structure and large scale ripples at their top. Two beds have rounded cavities partly filled by calcite which may well have originally been pebbles of gypsum. Limestone beds with similar structure, no bioturbation with the characteristic crystal balls and much greater thickness are found in more southerly positions in Jordan. They are well exposed in central Wadi Hisban southwest of Amman weathered to unusual tower-like structures and even more impressive in Wadi Wala forming a prominent step with water-fall in the river bed downstream of the crossing of Kings Highway. The massive and indistinclty stratified beds indicate an unusual transport, possibly produced by storms or by tsunami events connected to submarine earth quakes (Fig. 90). They formed when within the shallow shelf area much mud and sand was stirred up and transported by turbulent floods. As soon as conditions became more quiet the suspended material was deposited rapidly in a thick bed at once. The beds were of great thickness and had no endobenthic live.

During a tsunami event large amounts of sediment were eroded from the carbonate platform (ramp) and redeposited. Distinctive sedimentary feature of these tsunamites are due to their rapid deposition in thick beds. Tsunamis erode and rework huge amounts of sediments from the shallow marine and coastal settings and deposit them in these tsunamites. From Late Cenomanian shelf in Jordan the flood water eroded deposits of coastal lagoons which in part consisted of gypsum.

Fig. 90: Tsunami beds in Wadi Wala

Shueib Formation includes the transition from Cenomanian to Turonian as has been confirmed with nanno-fossils coccoliths that enables a biostratigraphic age determination. The formation is about 65 m thick and in the Amman region can besubdivided into the members 28 to 32. Layers with conglomeratic structure largely composed of reworked fossils are characteristic perhaps equivalent to “Wala Limestone” in the Wadi Wala - Wadi Karak area of central Jordan, resembling members 31 and 33. Some beds were deposited under oxygen poor conditions allowing no or little life on the sea-bottom. Since also oolites occur, the beds of member 30 could not have formed in deep water (Fig.91).

In central Jordan, Wadi Mujib, Wadi Karak and Wadi Hasa saline deposits are intercalated in beds which have been interpreted to be equivalent to partly uppermost Hummar and Shueib Formation. Here up to 2 m thick beds of gypsum are intercalated with clay beds, while further to the south they have been suggested to be represented by siltstones and sandstones. The influence of cyanobacterial mats in the accompanying sediment has been proven by a chemical analysis of the organic materials extracted from a dark bituminous layer. That influence is well documented by visible lamination of the limestones next to them. The gypsum was deposited in an evaporitic environment, in shallow saline ponds, and on tidal flats near the shore.

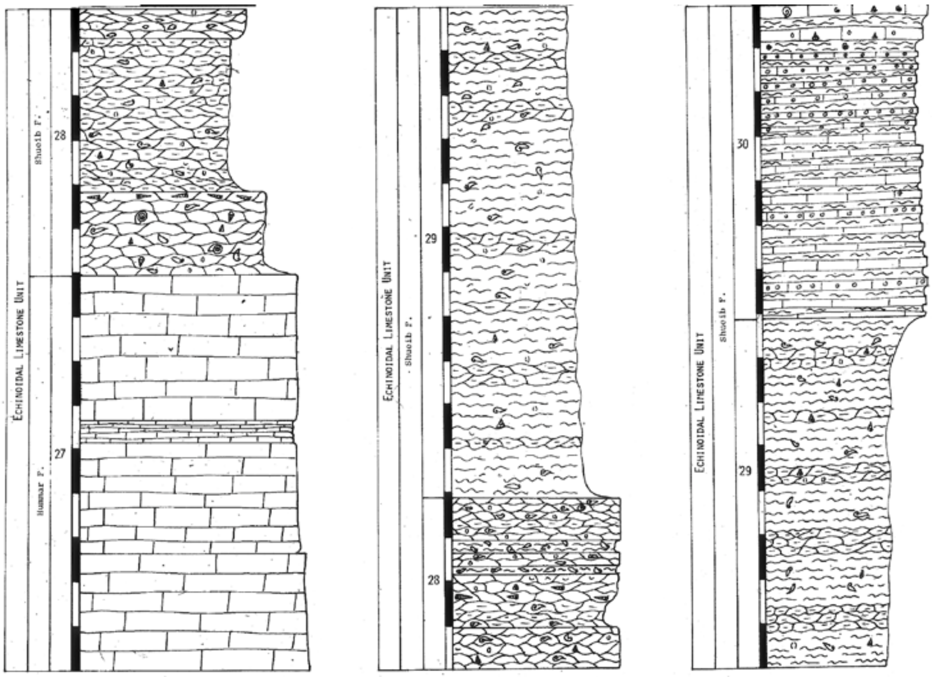

Fig. 91: Sketch of section of members 27 to 30 as developed at Um ed Dananir

Member 28 consists of 10 m of intensily bioturbated nodular limestone with *Ophiomorpha*-like crab-burrow systems not deformed by compaction. Gryphaeid oysters (*Exogyra*, *Rhynchostreon*, *Laevigyra*) are common in most beds. Other beds hold nerinean gastropods which indicate lagoonal deposition. Gastropods with their molds resembling aporrhaids and naticids, and bivalves of arcid, pteriid, protocardiid, and pholadomyid shape are present and give evidence also for deposition under normal marine conditions. Thick shells have usually been bored by sponges and bivalves. Some layers contain rudists.

Member 29 consists of 19 m of marl intercalated with some layers of nodular limestones with a *Thalassinoides*-like burrow network and tunnels with walls coated by pellets and about 5 mm width as well as an *Ophiomorpha*-like burrow network with longitudinally striated tunnel walls and widths of up to 12 mm. Gryphaeid oysters are common throughout and often preserved with both valves in place. Serpulid tubes attached to ammonites are found in some layers, other fossils are present as inconspicuous casts and steinkerns.

Member 30 is 15 m thick, well bedded limestone with intercalated marl with little bioturbation indicating that bottom life was less abundant then in the deposits below and above. Limestone beds in the lower half of the member are very fine-grained, almost lithographic composition. Some beds are oolitic and show inclined layers or cross bedding. In the upper half of the member, limestone beds acquire a chalky matrix with common ooids. Some beds hold numerous fossils which may be coarsely silicified. Among them are ophiurids, ammonites, bivalves with both valves still connected and aporrhaid gastropods. In other beds ammonites are quite large, and their living chamber has commonly been crushed by large vertebrates, here and there leaving clear traces of tooth impacts. Intercalation of marl and oolites in the upper part indicate formation near oolitic banks in shallow water. The sequence is well exposed next to and below the flexure at Um ed Dananir.

This member can probably be related to gypsum beds in Wadi Mujib-Wadi Karak area (Fig. 92). They have been described as connected to oolitic layers on one side and clay beds on the other. Just above them rudists in growth position have been encountered. A marine red bed as in Wadi Karak still needs to be detected at Um ed Dananir if developed here at all as it supposedly should.

Fig. 92: Wadi Mujib with its slopes holding Wadi as Sir limestones sliding on the gypsum bearing layers of Shueib Formation.

Member 31 consists of 5 m thick massive nodular limestone (Fig. 93). It begins with an oolitic shell bed overlain by a limestone with numerous bivalves preserved in living position. In the bed above bivalves of the same type as those in autochthonous position below werewashed together to form a conglomerate of steinkerns. A bed of nodular limestone follows and is bioturbated above containig oysters. It is overlain by a thick conglomerate of reworked nodular limestone, intercalated with some layers of autochthonous nodular limestones containing exogyrids, gryphaeids and plicatulids. The reworked nodules of sizes up to 20 cm served as holdfest to cementing oysters and a number of serpulid worms. Plicatulids and gryphaeid oysters lived between the pebbles. Many large ammonites and a few nautilids have also been reworked and deposited again as corroded steinkerns.

Member 32 consists of 3 m thick totally bioturbated marl with numerous irregular sea urchins throughout. The top layer contains many irregular sea urchins that had been reworked from the marl when the upper layers were eroded, after the echinoderms had been diagenetically altered to such a degree that they behaved like solid pebbles.

Member 33 is 5 m thick intercalated nodular limestone and limestone conglomerate with pebble size of up to 20 mm, well differentiated from the seaurchin marl below. It ends with soft marl above that contains small reworked pebbles as well as bivalve steinkerns, small ammonites and indurated burrow fills.

Member 34 is 11 m thick and consists of a lower part with banked nodular limestone and an upper part with clay-rich marl. The marl at the top of the member forms a conspicuous base to the limestones of Wadi Sir Formation above and is well exposed at Um ed Dananir and at the base of the cliffs to the north of Wadi Sir as well as at quarries to the west of Amman.

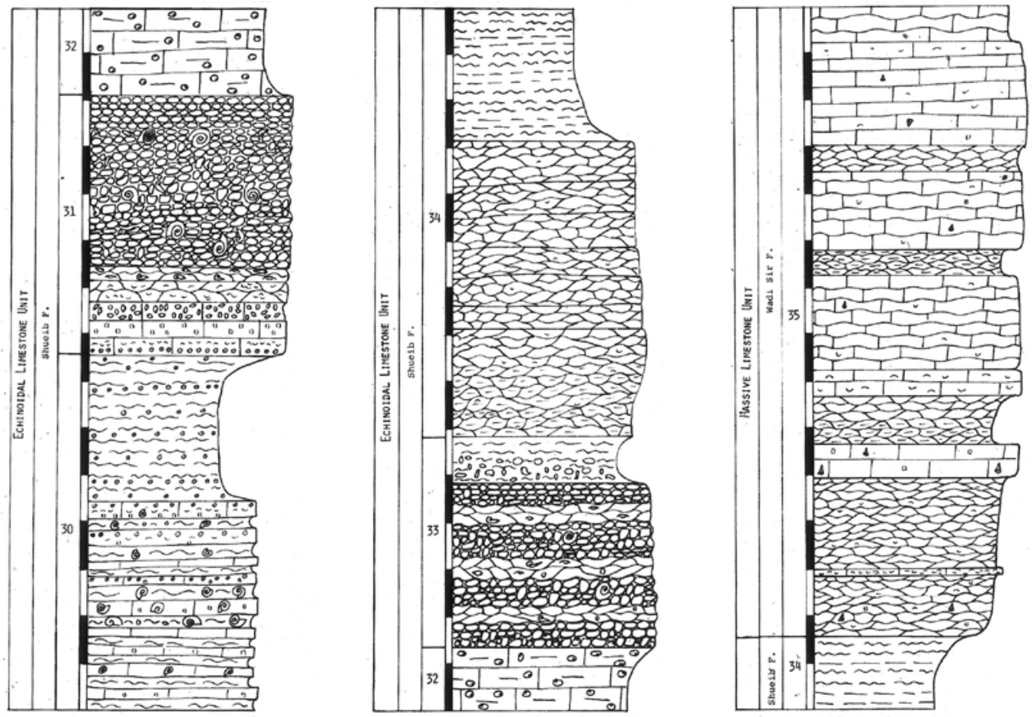

Fig. 93: Sketch of section of members30 to 35 as developed in Um ed Dananir

The lithographic limestone with many silicified small ammonites in some beds of the 15 m thick, member 30 reflect a distinct deposition differing from that of the members below with strong bioturbation and above with partly reworked fossils. Its depositional environment was in water with oolites forming nearby. Such a deposition with oxygen depletion has also been observed in central Jordan, occurring in the Cenomanian Turonian transition. Organic anoxic event due to stagnation and water stratification occurred over large areas on the Levant platform and around the time of Cenomanian Turonian transition also in other areas of the Tethys Ocean. In Jordan this time can be reflected in member 30. The oxygen poor environment was established in deposits of relatively shallow water, as is indicated by intercalation with oolitic beds which are an evidence for shallow shoal environment.

Brittle stars (Ophiuroidea) were probably present throughout the deposition of Late Cretaceous shallow water carbonates in Jordan. The elements of their skleton are calcitic and have a good fossilization potential, but are connected to each other with organic tissue that decomposes after death. Brittle stars, as well as the similar starfish (Asteroidea), are members of the Echinodermata and have five arms. But their mode of life and their behaviour differ very much from each other. Star fish are carnivorous and commonly feed on molluscs, while brittle stars catch small sized food particles from the water aided by fine ambulacral feet. Both are present in Aqaba. Brittle stars may be much more common wherever food passes by. They are more mobile by moving with their arms, while the starfish walk on their ambulacral feet and have to hunt their prey by doing so. In member 30 brittle star arms were noted with their many skeletal elements still connected to each other, while starfish still have to be recognized, but should have lived in the shallow sea here and in most other members as well.

Member 30 with its about 15 m of sediments as developed near Um ed Dananir may well represent equivalent in time to about 30 m of intercalations of gypsum beds with clay and bituminous marl that wererepeatedly described in the area of Karak. From here analysis of the organic content as well a the composition of carbon isotops have been correlated to global changes during the Cenomanian-Turonian transition. The excursions of the composition of stable isotopes of carbon were measured from Wadi Karak in a sequence equivalent to member 30 intercalated between the between the limestones of the top of Hummar with member 29 and the ammonite rich base of member 31 north of Amman in near Wala limestone.

A special event regarding the plankton was noted in the occurrence of some beds with many calcispheres (*Pithonella*), probably representing calcareous dinoflagellate cysts. The data interpretation of the analyzed rocks would also rely on a number of unknown factors including the quite incomplete kowledge of the position of the shore in the south and southeast during this period which supposedly spans a time of 1.2 Million years and also of the amount of subsidence of the continental margin during that period. One of the clay layers connected to the younger of the two gypsum deposits was interpreted to be the equivalent to a deep water red bed that was noted at different places in Tethys deposits. This about 1 m thick red clay above the upper gypsum bed and below the “Wala limestone” bed has been assumed to be somehow correlated to beds of similar composition and similar age which form in deep water, even though it was deposited in a shallow marine environment.

Member 31 and 33 consist to a large part of reworked material, and in comparison to the Karak area it appears to be of similar composition as a unit called Wala Limestone. The fine marly limestone of member 32 with many sea urchins was a carbonate sand that was totally bioturbated to almost uniform consistence by the feeding activities of the heart-urchins. Within this sand the corona of the urchins was transformed into a massive calcite crust and the interior fill of fine sediment was lithified before they were winnowed from the top part of the sand, to be enriched here on the sediment surface. This layer was then covered by debris that came from reworked deposits which would have presented nodular limestone after complete diagenesis. It resettled those components which became more solid during early diagenesis with first cementation, and the clay-rich material between them was washed away.

Member 31 has quite large steinkerns of *Nautilus* which is the only still living cephalopod with an external shell. The study of its mode of life helps to understand extinct ammonites. The individuals from basal Turonian are larger than modern species, but otherwise very close to them in shape and construction. The environment in which Jordanian individuals lived were quite different from that of modern *Nautilus* since their living environment lies on the seaward slopes of tropical coral reefs in the tropical Indo-Pacific Ocean for example near the Philippines or New Caledonia. But Shueib *Nautilus* probably also lived by hunting crabs and cracking them with beak-like jaws, as is known from living *Nautilus*. The collection and preferrence of food by the ammonites is not well known but they were probably also carnivore. But neither the shape and number of their arms nor the function of their beaks have been reconstructed conclusively. Nautilus has a chambered shell in which the chambers are connected to each other by a siphonal tube. Its position and composition differs from that in ammonites, but its general function was probably quite the same. The visceral mass of the body continues in a fleshy tube that lies within the siphonal tube. The outer tissue layer of the fleshy siphon (mantle tissue) acts as pump and sucks water trough porose parts of the sipuncular tube. This process is not all that simple but in its general way, the same in all cephalopods, with a chambered shell, thus also the *Sepia* with internal shell that still lives in the Gulf of Aqaba. The water in the chambers is close to that of normal sea water in salility and composition when the cephalopod has secreted a new partitioning (septum) and thus a new chamber and together with it a new section of the siphonal tube that crosses its interior. Pumping of water is due to differences in salt concentrations along the walls of the siphuncular tube, which is semipermeable. Thus water can migrate through them more easily than salt. The mantle tissue of the fleshy tube secretes a mucus (extrapallial liquid) in which the salinity is controlled. When water is pumped from the chamber, the salinity of the mucus is increased and water sucked from the chamber due to the osmotic pressure built up due to the differnce of salt on both sides of the siphon wall. When the chamber needs to be flooded the salinity in the mucus is lowered and salty water in the chamber is diluted. In *Nautilus* this process is slow, but sufficientl to balance with chamber uplifting the weight of the animal.

Ammonites differ regarding the siphonal tube that lies in marginal position, is narrower than that in *Nautilus*. It has a thin organic construction contrasting the thick organic tube surrounded by calcareous material in *Nautilus*. Also the shape of the septa between chambers differs by having a compexly folded attachment to the inner wall, while it is smooth and simple in *Nautilus*. Thus in general their construction resembles that of *Nautilus,* but it may well have been different in function regarding the speed in which water was pumped from the chambers and changes in boyancy carried out more rapidly.

Hoplitoidea and Anthracoceratoidea characterize the ammonites occurring in the Cenomanian Turonian shallow shelf water deposits in Jordan. In case of the most common ammonite of the genus *Neolobites* of the Hoplitoidea from the Cenomanian the shell is variable with strongly compressed to slightly inflated cross section and small, shallow umbilicus. The outer margin of whorls is narrow-trapezoidal with sharp shoulders and in some species ornamented by fine crenulations. The suture is simplified compared to that of other ammonites and consists of rounded, narrow lobes and wide rounded saddles. Whorls have variable ornament and are smooth or have flexuous ribs. Some are depressed with a small umbilicus others have a larger umbilicus and have more angular whorl section and stronger ribs. Possibly some of the variability is due to dimorphism, with smaller males (up to 13 cm in diameter) and larger females (up to 16 cm in diameter). And the shells of both sexes may have differed somewhat in their ornament. *Neolobites* is restricted to Middle to Late Cenomanian and lived in shallow marine environment especially in the southern Tethys on the shelf of the Nubian continent.

Hoplitoidea represent a superfamily of the ammonites that can belong to the Perisphinctina of the Ammonoidea that represents one of the two groups which evolved during early Jurassic from the only surviving ammonite group of a crisis that almost exterminated ammonites in general. This suborder is distinguished from others by the evolution of the ventral part of the suture line. Among the Perisphinctina there is a common scheme of splitting the inner lobe and the following saddle.

Vascoceras and *Mammites* belonging to the Acanthoceratidae represent a family of ammonites considered to be related to the Hoplitoidea by some and not by other amonite specialists. They evolved in the Cenomanian and had several species living in the Jordanian shelf sea at Cenomanian and during Turonian. Most species have strong nodular ribs with their umbilicus narrow when young and wide when older. *Mammites* has ornament of single rounded nodes in the few axial ribs. Some species recognized from the Turonian of Jordan belong to *Fagesia* with inflated whorls, very wide and deep umbilicus with a nodular raised corner. Individuals can reach rather large size of almost 40 cm. *Choffaticeras* is more disc-like and it has a narrow almost keeled side and also narrow umbilicus appears to have several species living in the Turonian of the area. *Thomasites* has rounded whorls with few nodular ribs and relatively narrow and umbilicus with rounded sides from the Turonian. Its suture line is simplified.

Turrilites is a family in itself, quite distinct from the Acanthoceratoidea since it is helico-spirally coiled resembling in shape a gastropod. But the chambered phragmocone with the complex sutures of the ammonite type distinguishes it clearly.

The layers in Shueib Formation which are rich in ammonites are perhaps equivalent to Early Turonian, ammonite rich horizon, as have been documented to occur in the sequences on the Sinai and the Negev Desert. Here it has been interpreted that a stratigraphical gap separates last Cenomanian deposits from those of the Turonian, with some biostratigraphical zones missing. This gap was interpreted to have been produced by a rise in sea level. In the Amman area only reworking of sediment can be documented, with some layers deposited from the reworked fossil steinkerns of bivalves and cephalopods. In that interval between the end of Cenomanian and early Turonian a trans-Saharian epicontienetal seaway was reconstructed connecting the Tethys across the African continent with the southern Atlantic Ocean and through which some of the ammonites found here migrated.

Planktic Foraminifera of the Cenomanian to Turonian limestones are represented by species of *Hedbergella*, *Heterohelix*, *Globigerinelloides* and *Whiteinella* which mainly lived in the upper water column. The morphology of the test of the foraminifers varies, but for their classification two features must be considered: The arrangement of the chambers and the type of the aperture. Foraminifera in general differ in details but their basic design is similar. Approximately 4000 living species of foraminifera may exist but the life cycles of only 20 or so are known, and most species live on the bottom of the sea. Reproduction, growth and feeding of species differ from each other but the alternation of sexual and asexual generations is common throughout the group. *Hedbergella* has rounded chambers with regularly increasing size attached in a spiral with pores in tubercles on the surface of the test. *Whiteinella* looks similar but has a more rapid increase in the size of the chambers and a larger aperture in its umbilical region, and *Globigerinelloides* has an even more rapid increase in chamber size and consists of fewer chambers (5-6). The test of all three genera resembles that of living *Globigerina*. *Heterohelix* in contrast is of triangular shape with rounded chambers arranged with increasing size not in a spiral but in an alternating row.

The reworked nodules and ammonites in members 31 and 33 were sometimes settled upon by tube building worms of the Serpulidae. The annelid worms of the Polychaeta secrete tubes which in case of many species are calcitic and can thus be preserved quite well. They were not common in the Cretaceous shelf sea of Jordan. Their mode of life can be studied on living species in the Gulf of Aqaba. They lead a sessile life attached to substrates and filter food from the water that passes by with the tentacles on their head.

The determination of gastropods and bivalves from the fossils consisting of internal consolidated filling of the internal cavity and not with the actual shell is problematic. Also that of the impressions, often preserved as molds on which the original outer ornament is partly preserved during compaction is difficult. In case of gastropods with short shells with rounded body and rapid increase in whorl dimension they have often been considered a member of the Naticidae. That determination can only be made more plausible when their activities have also been preserved in shape of drill holes in the shells of bivalves found nearby. They then feed on the tissue of their prey. Often species of the totally unrelated Nertidae have been misinterpreted to belong to the *Natica* relation. Actually they represent a different subclass of the Gatropoda with usually a calcitic outer shell layer. A member of the Neritidae of the genus *Otostomia* was determined from impressions in the dolomitic Cenomanian limestone of Isteffena, where it lived among the rudists. Their mode of life differs considerably from that of the Naticidae. They feed by scrapinng custs of algae from hard surfaces aided by the partly minerlized teeth of their radula.

Shells with more elongate shape and regular increase in shell hight and whorl width are often placed with *Cerithium* and relation. Their determination to the species and even the genus is also problematic, even when part of the ornament is preserved. As long as the shape of their early ontogenetic shell is not known their determination remains insecure, due to much convergence. *Turritella* here presents an exception due to its slender shell shape, the simple aperture and especially its occurrence with masses of individuals in a single deposit. Also Stromboidea can often be recognized, in case their fully grown shell were fossilized including the widened outer lip of the aperture and the presence of spines. In case of the largest gastropod that occurs quite conspicuously in some Cenomanian beds of Jordan the place in the taxonomic system can not be determined. It may represent a member of several different groups including Stromboidea but also resembles Cassoidea or Muricoidea of the Latrogastropoda. It has been determined as *Harpagodes* or *Strombus* in Cenomanian deposits of Sinai - a rather helpless determination. The wide range of shell shapes of species belonging to the Neomesogastropoda and Neogastropoda of that time is well represented by well preserved species as from the North-American Ripley Formation. Here they document much convergence of shell shape within the species of different groups which can be distinguished by the characters and shape of their protoconch (early ontogenetic shell). A similar determination can, in Jordan only be carried out of some layers of Amman Formation.

Small opisthobranchs may have the shape of *Olivella* and may be mixed up with them while the shape of the protoconch clearly distinguishes them from each other. The first has the character of the Heterostropha that is initial sinistral coiling, which changes into dextral coiling with onset of the shell of the benthic animal. Large shells of that type are present with *Actaeonella* which can also be determined by shell shape and folds on the columella. The same is the case with *Nerinea* as was stated above. In case of low trochispiral shells for example members of the Architectonicoidea among the Heterostropha closely resemble some members of the Trochidae of the Archaeogastropoda although and not all of hem arerelated to each other, except that both represent gastropoda.

Wadi Sir Formation (Massive Limestone Unit) has its type locality on the slope between Wadi Sir and Amman and is here about 110 m thick with members 35-38 (Fig. 94). Deposition occurred predomiantly in the shallow sea. At the top of the formation, change to chalk occurs. Here the transition form Turonian to Coniacian took place. The deposits of Wadi Sir Formation in central Jordan have been described as of similar thickness ranging between 100 and 150 m.

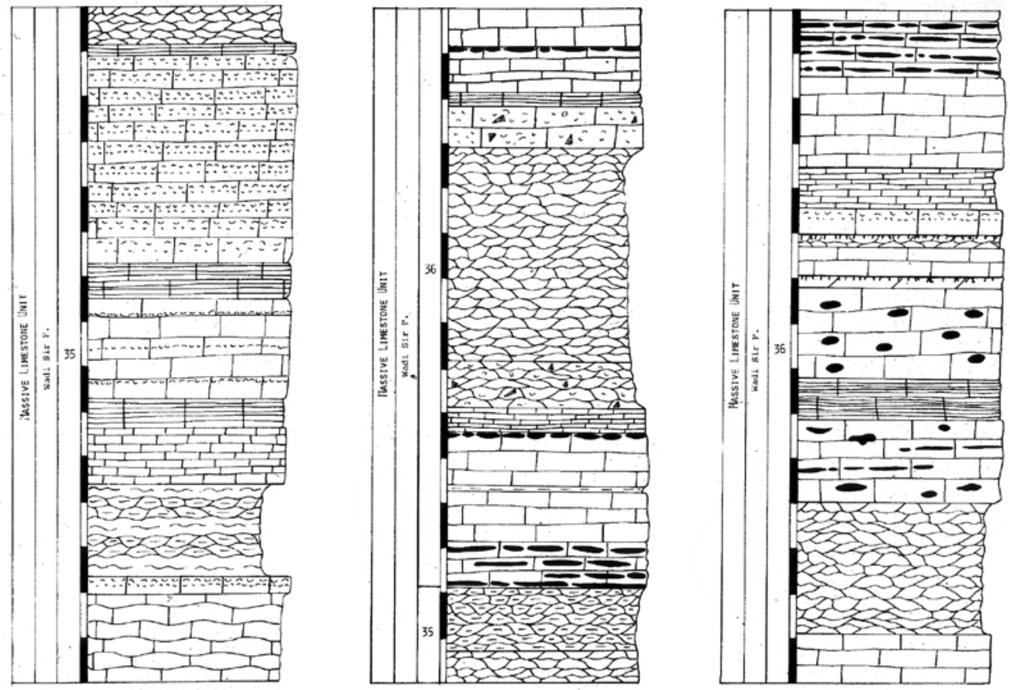

Fig. 94: Sketch of section of members 35 and 36 as developed above Wadi Sir

Member 35 is a 30 m thick intercalation of nodular limestones and banked limestones. With the exception of a few laminated beds in the upper central portion of this member all beds are bioturbated. A few bivalve shell beds are present commonly showing preserved grading with larger shells below and smaller ones above.

Member 36 is 37 m thick, distinguished by laminated limestone beds which contain 1-4 cm thick crusts and flat nodules of chert, and end with an oolite.

Member 37 consists of 20 m of limestone (Fig. 95). Its lower part is intercalated bioturbated nodular limestones with flint beds, oolites and laminated limestones. A few dolomitized bored hardgrounds indicate terrestrial intervals of non-deposition and erosion and are associated with intraclast layers. The top part is nodular limestone with conglomeratic layers, intraclast beds and oolites. The space between reworked limestone pebbles was settled by rich fauna of regular and irregular seaurchins, as observed at Ras el-Ain in the City of Amman. Rapid facies changes occur both in vertical and horizontal directions. Layers rich in fossils especially, gryphaeid oysters (*Exogyra*) and signs of abundant benthic life, change with others layers with no or little sign of the activity of endobenthos. In the quarry at Ras el-Ain also ammonites occur.

Member 38 consists of 20 m of massive limestone (Fig. 96). Beds consist of shell debris and calcareous sand. Thick shells of bivalves are commonly strongly bored by sponges. In the uppermost beds rich fauna of gastropods (turritellids, actaeonellids, neritaceans, and several neogastropods) and bivalves are found with their shells coarsly silicified. Here also some seaurchins are found.

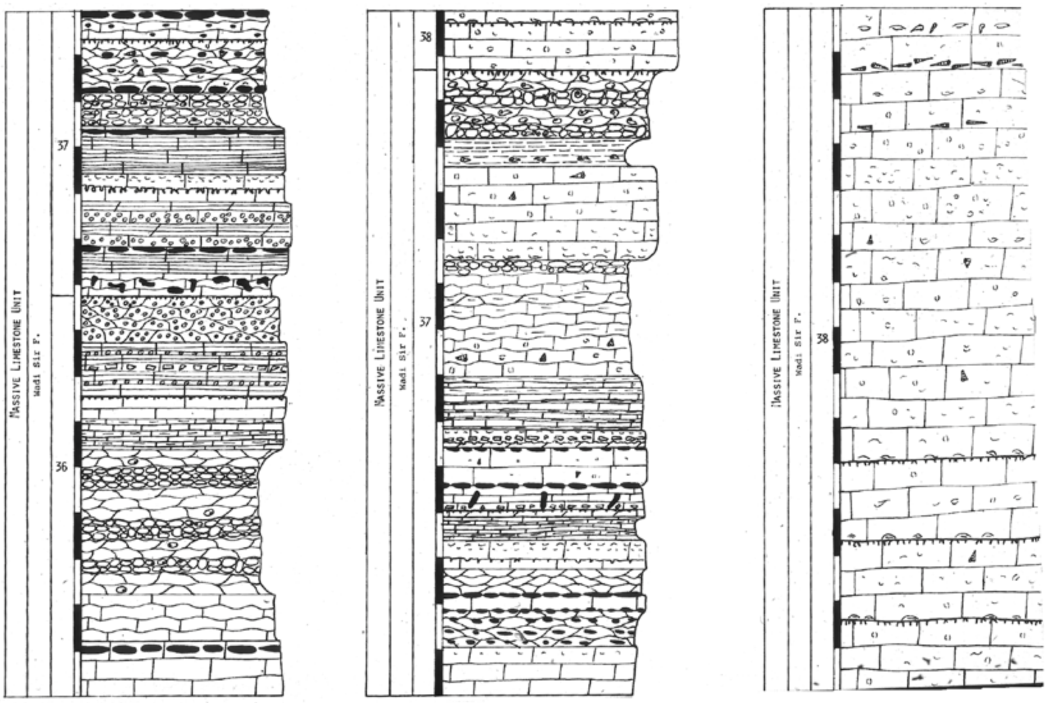

Fig. 95: Sketch of section of members 36 to 38 as developed above Wadi Sir.

Turritella is a characteristic gastropod with slender conical shell and a quite distinct mode of life since Cretaceous time. The gastropod burries in the loose sand or mud and keeps contact to the surface of the sediment by the tissue of its mantle forming tubes. With the cilia of its gill it produced a current that sucks water in through one opening and blows it out by the other. That way water is pumped across the gill that extracts cells of algae (phytoplankton) from the water in a similar way as is done by bivalves. These cells are concentrated into mucus ribbons that migrate towards the head and are here taken hold of by the snout and the radula teeth of the snail. Thus species of the *Turritella* relation can form populations with many individuals living close to each other, evidencing the presence of water passing by with much phytoplankton in it. It is no surprise that *Turritella* occurs in large numbers in the transitional zone from Wadi Sir Formation to the overlying chalky Ain Ghazal (Um Budran) Formation. Turritella presents evidence for the availability of soft bottom substrate to hide in and rich phytoplankton in the water above at the time of its life.

The transition from Cenomanian to Turonian in Mujib and Karak areas in central Jordan includes saline deposits of gypsum connected to red and green clay in the lower deposit and to fine dolomite beds in the upper one. Both deposits of saline lagunes are separated from each other by limestones and overlain by a shelly bed on which rudists grew and were preserved in growth position. Quite similar transition from Cenomanian to Turonian connected to greenish clay, saline deposits and rudists found in growth position can be found in Ajlun in northern Jordan. But here the gypsum is not preserved, only collaps structures and cellular dolomite are found. Further in the south of Jordan this facies of saline lagunes changes to lagunes influenced by fresh water of rivers coming from Gondwana. Near Petra sandy deposits intercalated with coaly ones have been observed. Such changes from saline deposits in restricted lagunes to open sea reefs and lagunes influenced by fresh water during the Cenomanian Turonian transition can be observed today for example along the coast of the Caribbean Sea of Columbia. In geological sections, this change can also be observed in one and the same locality, but in stratigraphical different position.

In North Jordan Wadi Sir Formation can not be recognized and the transition from Cenomanian to Turonian lies in shallow water with lagunes and rudist banks and may even have occurred when the area or part of it was an island. With the begin of chalky sedimentation of the Belqa group the area became part of the uniform sea that covered the Jordanian shelf from north to far south.

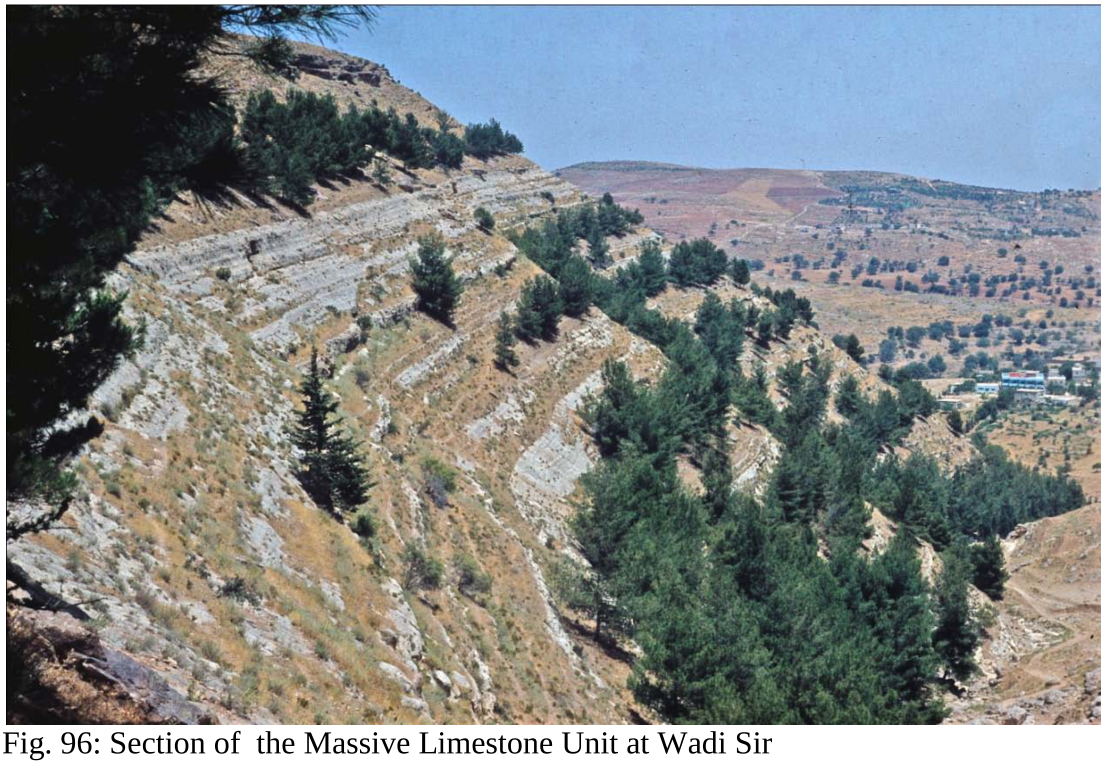

Fig. 96: Section of the Massive Limestone Unit at Wadi Sir

Between the castle of Rabad and the village of Istafena to the north of Ajlun limestones are exposed which represents deposits of extensive rudist banks and of lagunes. During early Cenomanian sedimentation here resembled that of the Amman area with nodular limestone of which about 70 m are exposed in the area of the town Ajlun with a speciality of a layer with numerous brachiopods of the *Terebratula* type, equivalent perhaps to Suweilih Formation near Amman. Above that equivalents of Naur Formation of about 65 m in thickness with *Cyclolites* like single corals and large foraminifers of *Praealveolina* type formed. The succeeding about 65 m of nodular limestones hold ammonites and among them the characteristic *Turrilites* with gastropod-like helico-spiral coiling. It lived during Late Cenomanian and indicates that these deposits are probably equivalent to the Fuheis Formation near Amman.

The limestone above is quite pure. Obviously suspension of clay from the rivers coming from Gondwana continent did not reach this area. A series of about 35 m in thickness of limestones composed of skeletal remains often those of rudists is developed (Fig. 97a,b). The lower part of the limestone was deposited during the Cenomanian and the upper during the Turonian which is well docmented by rudist species. Species belonging to the Radiolitidae and Caprinidae represent the main frame producing elements of the rudist bank (Rabad-rudist member) which is about 15 m thick. While species of the first represent coral-like elevators that grew singly or as attached to each other in thickets. The caprinid species consist of recumbent individuals that never attached to each other or to the substrate. In the Rabad member a layer of about 2 m in thickness is locally dolomitized.. The coarse reddish dolomitic rock preserves the rudists composing much of its original construction quite perfectly. These fossils can be studied very easily since the farmers of the region have used the rocks containng them to construct the walls around their orchards (Fig. 98).

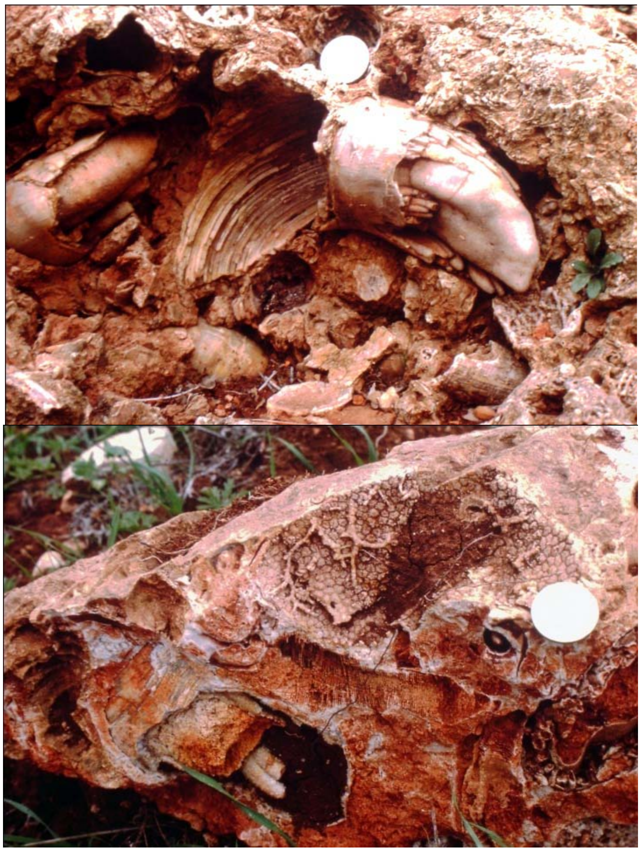

Fig. 97a,b: Caprinula and coral From Ajlun area

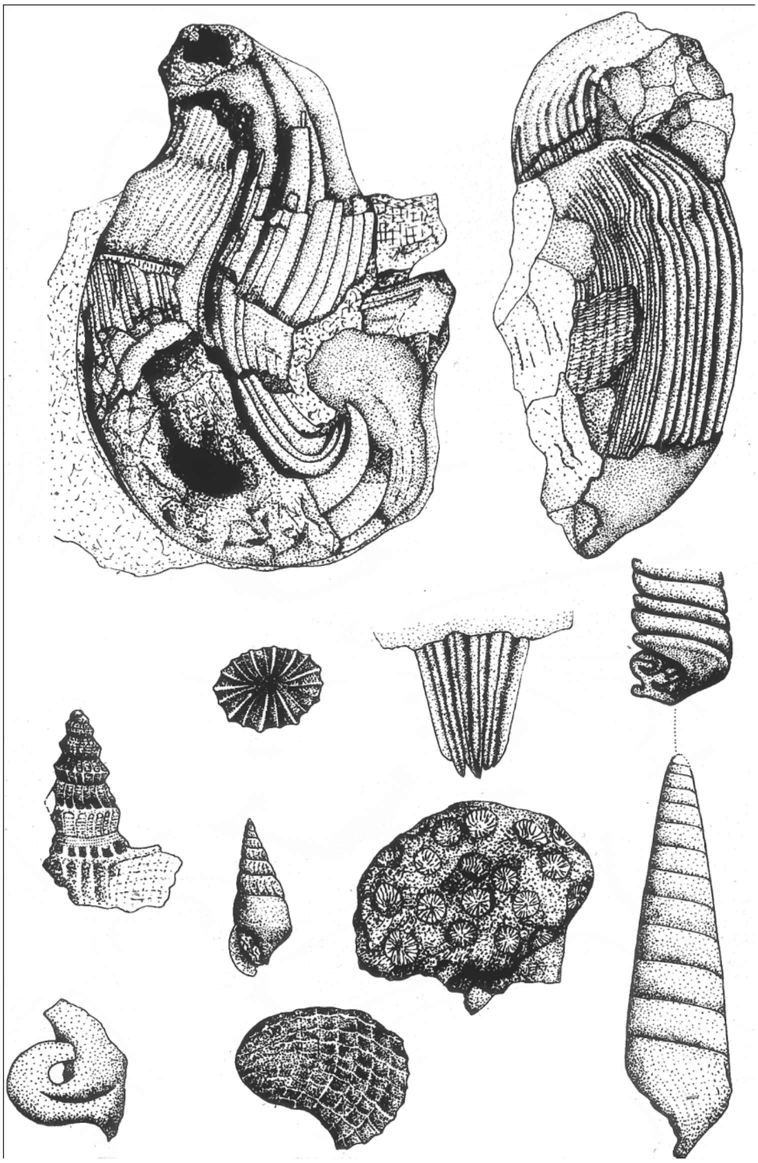

Fig. 98: Drawings of some fossils occuring in the Cenomanian Rudist limestones at Isteffena

Among the rudists *Caprinula* has two horn-like valves connected to each other by teeth, one in the right and two in the left valve. The organic ligament that was situated between the teeth caused a slight push to open the valves for a narrow slit when the bivalve was active. The slit could only open for a short distance due to the teeth fitting in their sockets and leaving little space for the valves to open. The valves were held together by long muscles attached to walls within the shell lumen. The shell valves are of similar size but have different curvature, sometimes similar to each other and in other cases quite different from each other. The outer shell layer below the predominate organic periostracum was a thin transparent calcitic layer. The inner thick shell layer was originally aragonitic and contained many open tube-like canals which were opened along the shell margin. Only deep within the shell these tubes contain septa. Into these round canals the bivalve extented tentacles of its mantle. Some of the larger canals reach far back and are up to 25 cm long. These mantle tentacles most probably housed algal cells as symbionts and became illuminated in the shallow sea with the light prnetrating the thin outer calcitic shell. Similar symbiosis between bivalve and unicellular green algae is found in the modern *Tridacna* that lives in Aqaba in the illuminated waters of the lagoon.

Radiolites has a rather different shell that stood upright on the bottom with a conical lower and a lid-like upper valve. The ligament connecting the valves to each other lay in a fold formed by the outer calcitic shell layer in a position between the long and deep gooves into which the teeth of the flat lid-valve could be fitted. The ligament attached to the hinge between the teeth of the smaller plate and was an elastic element that caused the valves to gap a little. Since the two large teeth of the smaller valve fitted into deep grooves on the conical valve which were only a little larger than the teeth, the elastic ligament could produce only a very restricted gaping of the valves during the activity of the bivalve. The large shell thus had only a maximum gap of a few millimeters. Rotation of both valves against each other was not possible. Both valves were pulled together by two strong muscles which were attached to the lid valve and in special grooves next to the tooth gooves in the conical valve. When muscles relaxed the valves opened, not only by the elastic ligment, but also by hydrostatic pressure produced by the mantle.

The preservation of the rudists of the Cenomanian *Caprinula* and *Radiolites* is such that original bore holes in the shell are well preserved since they have become filled with dolomitic material while the original shell dissolved. The borings belong to the network of small round cavities connected to each other by tunnels as they are produced by the boring sponge *Clione*, club like vertical cavities with their smaller end toward the original surface of the shell as produced by boring bivalve and U-shaped tubes as are nowadays etched into shells by the polychaete worm *Polydora*, and others. In thin sections of basically unaltered limestone produced near the rudist-growth skeletal elements commonly have a fine grained rim. Such transformation of shell material of different original composition and structure into micrite is caused by fine algae, fungi and especially boring cyanobacteria which infested the skeletal particle. These rims form on particles in well illuminated water and can thus be interpreted as indicators of the original depth and clarity of the water. Calcareous algae belonging to the Rhodophyta (coralline algae) are part of the rudist banks and present evidence for its place within the illuminated shallow water. A regular sea urchin *Goniopygus* also occures relatively commonly in the Rabad rudist member.

The following lagoonal limestone is about 20 m thick. It has several thin clay beds intercalated with strong lithological difference to the pure limestones below and above. Since the dense white limestone has been used for building stones large surfaces of the thin clay beds have become exposed and document mud crack surfaces. This clay probably arrived here through the air and was deposited in a lake or brackish lagune on land. This mode of deposition from dust blown here is a likely source since the water surrounding the island was clear and the limestones formed around it are pure $CaCO_3$ with extremely little clay content. Many of the fine grained limestones have thin stylolithe sutures.Their formation in general indicate the purity of the limestone. The gastropod *Trochactaeon* with about 6 cm high shell occurs here commonly and is locally very evident since its shell in some layers is silicified and weathered out. Within the same environment hipporitids formed thickets attached to beachrock formed at lagoonal shores. Cross- bedded calcareous sand was tranferred along the beach to beach rock.

Among actaeonellid shell debris in the shallow lagune lived a requienid species that retained the ancient constructional morphology of earlier ancestors of the rudists. *Apricardia* a small horn shaped rudist of the *Diceras* type is common in some layers within the lagune at the Ajlun rudist bank environment. The right free valve forms less than half a whorl and is flatter than the left with attached valve which is the larger one with about 3 cm in maximal diameter. This genus was also noted in southern Jordan. The mode of life may not had differed much from that of other sessile bivalves, even though it is considered to represent a relative of the specialized rudists. It lived on hard substrates in the shallow lagune.

Lagoonal limestones can be totally churned by bioturbation and in that case usually have many miliolid foraminifera, which are pocellaneous benthic protozoa with a smooth shiny calcitic shell. They tolerate harsh environments where water can have more salt than usual or can become warmer than is the rule. In the modern reef lagune at Aqaba many individuals of Miliolidae live near the beach in and on mud and algal thickets often within the intertidal zone. Miliolid foraminifera can also tolerate oxygen depleted bottom water as may occur periodically on the muddy ground of a lagoon.

Above the Rabad rudist layer and below the *Hippurites* growths, thus perhaps beteen Cenomanian and Turonian deposition, the area, at least locally, fell dry and islands formed extending above sea level. The exposed limestone partly dissolved, caves formed, collapsed to pits and karst-like solution structures present evidence for a period during which fresh water dissolved rocks. The karst phenomena were subsequently covered again by fine grained limestones as formed in the lagune.

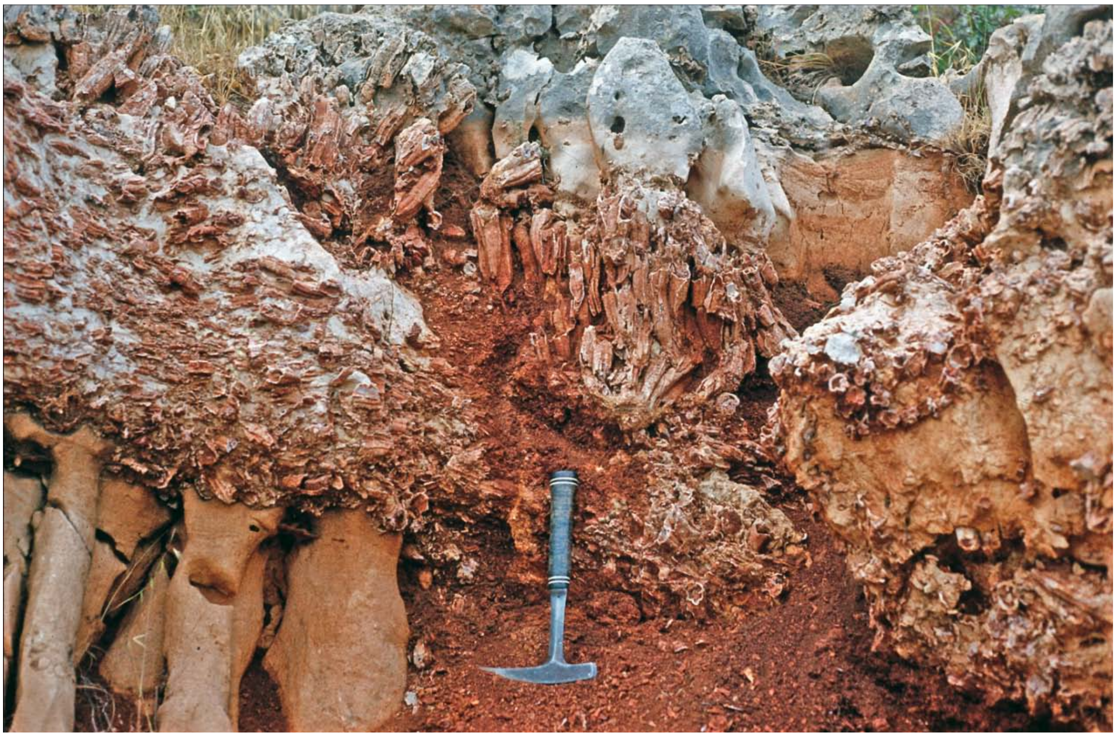

Fig. 99: Hippurites growths on carbonate sand-beachrock (Istafina area).

Within the lagune *Trochactaeon* lived in the mud and *Apricardia* settled shell debris. Hippuritids formed thickets attached to beachrock along lagoonal shores and attached to cemented shoal debris (Fig. 99). The stratigraphic position of the Turonian in these shallow water and lagoonal limestones is determined when *Hippurites* is found. This rudist has commonly been silicified and can be preserved more or less in living condition, as tumbled down colonies of several individuals together, and also as wave washed debris (Fig. 100). The *Hippurites* has a rather thick shell and on its smaller lid-like valve an outer layer with cellular porous structure. The central part of the upper valve is thick and massive, the marginal part is thin and was elastic and transparent. In the living bivalve the margin of the mantle was atttached close to the shell margin und was probably not withdrawn into the shell lumen when valves were closed. This is documented by the imprints of the veins of the mantle margin forming branching outline on the shell surface. The ligament is very thin and lies in a fold in the wall of the conical valve that has its position between the grooves to hold the teeth. It was like a thin ribbon of rubber which held the valves together, but was not sufficiently strong to push them open. Also the two teeth of the hinge are large and wide and had strong and short muscles attached to them. They fit well into grooves of the conical valve. When the muscles pulled the valves together they could open again only by rotating the lid valve a little and push it up, probably with the hydrostatic pressure of the mantle. The shell of the larger valve is relatively thick with a wide outer calcitic layer and a narrow inner aragonitc layer. In the active *Hippurites* when fully covered by water the mantle margin expanded onto the lid valve and when the bivale retracted into its shell, for example during low tide, the mantle retracted including the tissue of the siphons for ingestion and egestion of water into the mantly cavity. The lid valve fits tightly in the margin of the conical valve sealing the shell perfectly. The mantle exposed on the surface of the lid valve and also still below it provided a large surface for the symbiontic algae contained in it to exploit sunlight. During activity the water used for respiration passed the gills by the two siphons one serving for the water to enter and the other to leave the cavity. In the large shell a comparatively small animal with the mantle visceral mass produced septa which closed off surplus space. The conical shells were rapidly growing and extended well above the surface, away from their anchor point, which was on hard substrate, commonly on beach-rock ledges.

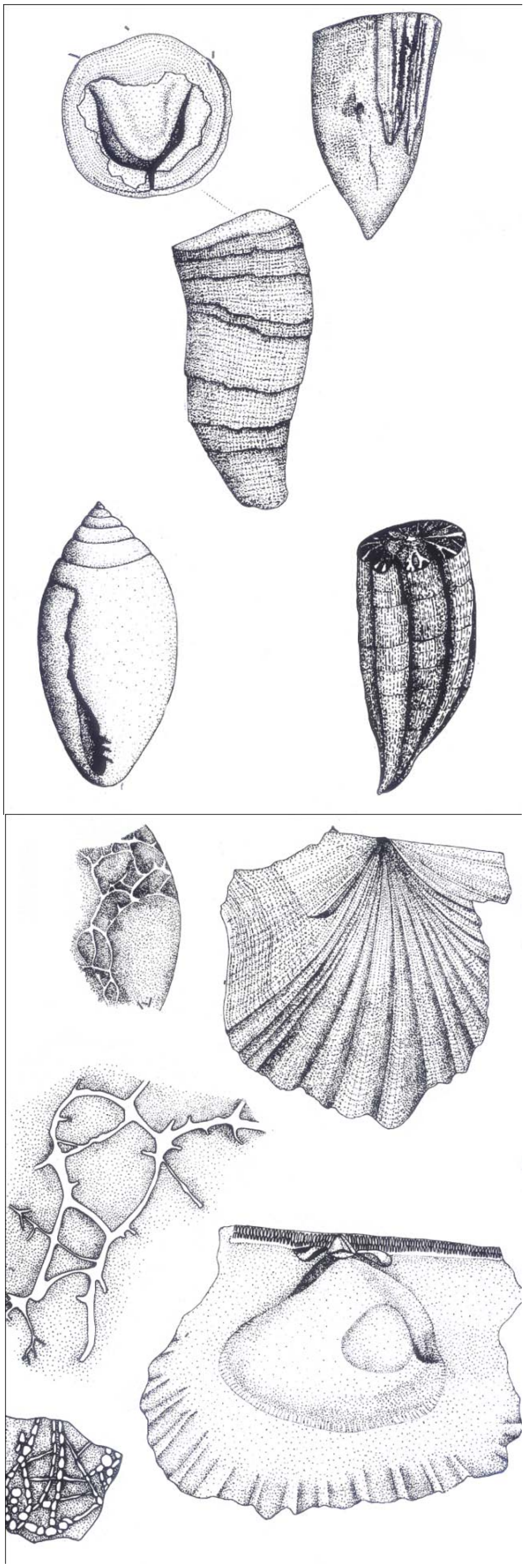

Fig. 100: Fossils from the rudist limestones of Istafina, on the right side a radiolitid rudist from the Cenomanian, Trochacteon and Hippurites from Turonian, on the left side a large bivalve from Cenomanian rudist beds with the shell bored, probably be sponges.

The layer with *Hippurites* in the area of Istafina was overlain by about 30 m of laminated limestone before the change to the chalk of Ain Ghazal Formation was exposed. Thus, the total thickness of deposits here near Ishtafina, related to the deposition of Wadi Sir Formation near Amman, is 55 to 65 m, amounting to only about half. Since both deposits formed in very shallow water subsidence in the Ajlun area was only about half that in the Amman area. Coniacian chalk above is evidence for the end of the shoal environment after Turonian.

Comparable rudistid banks forming reef-like structures have been described from the former shelf margin exposed at Carmel mountain just southeast of Haifa in Israel. The rudist beds here are 11-25 m thick and resemble in composition Rabad rudist member in Istafina. While these Cenomanian rudist banks occur along the shelf edge in the Carmel region, here and further to the south along that margin also Turonian reefs have been noted mainly from the subsurface including patch reefs of hippuritids with a total thickness of the reef belt at the Carmel of about 160 m. These rudist banks have been interpreted to follow the shelf margin at the edge of the slope towards the Tethys ocean. In the Cenomanian rudist growth could even be connected to islands produced by volcanic eruptions, since the Carmel pyroclastics have been found to be connected to shallow marine environment.

Near Jerusalem an upper Cenomanian to Turonian sequence of about 120 m in thickness overlies platy lagoonal limestones of the Cenomanian and underlies chalks of the Coniacian –Santonian. These limestones contain layers with rudists and layers with gastropods, either *Trochacteon* or *Nerinea*. Here deposits lie about 100 km further to the south and as displaced by the fault in the Jordan Rift and could represent the continuation of the Ajlun banks to the west.

South Jordan subsided less during Cenomanian times than North Jordan, and therefore deposits in the south are thinner. In SE Jordan rivers discharged their sand into the sea and sediments produced at or near the beach. In the Mujib-Karak region of central Jordan Cenomanian measures around 270 m. During Turonian subsidence was similar to the Amman region with a change into Coniacian chalk after about 140 m of shallow water deposits had formed. At Ras en Naqab about 145 m of sedimente were documented including fluviatile sands intercalated with marine deposits. Often the shore lay near the exposures at Ras en Naqab. Subsurface data from the Sirhan area in SE Jordan indicate that Cretaceous here is only 70 – 170 m thick with its base at about 450 m below surface overlying Silurian sandstones. During Turonian fresh water deposits with a flora of Angiosperm leaves was found in the Negev area, which may be of similar age as the angiosperm leaves repeatedly reported from the “Nubian Sandstone” of SE Jordan.

Along the escarpment in the south in Batn El Ghoul area, the sea, during Turonian, did not advance as far as during the basal Late Cenomanian, and marine limestones are unconformable overlain by fluvial channel sandstones, which thin north-westwards. The river sands are covered by a marine sequence of sandy limestone, dolomitic sandstone and laminated clay and limestone at the top. Thus the shore of the Turonian shelf sea in Jordan lay in the area of Ras el Naqab for some time. It was documented that from Albian to Campanian Cretaceous sandstones, deposited in SE Jordan are composed predominantly of sand that was eroded from other earlier sandy deposits and deposited in shore environment without much tidal influence. When the sea withdrew the coast was dominated by deltaic deposits and when the sea returned the area was flooded and lagoons and beach barriers formed. The analysis of the advances of sand from the continent into the sea and oppositely the sea onto the coast suggested that the land slowly subsided quite regularly, while the level of the sea globally changed, and that apparently happened eight times between basal Cenomanian and top Santonian. Climatic change was not deduced from these deposits, but they can be interpreted from plant fossils.

From similar outcrops in the Negev desert of South Israel leaves, for example of *Nymphaea*, *Nelumbites*, *Viburniphyllum*, *Magnoliaephyllum*, *Debeya*, and *Archaecypera* were described which were deposited on the bottom of a large freshwater lake. Some of the taxa are common to those found in Upper Cretaceous floras of the northern shore of the Tethys; others are common with coeval floras on its southern shore. *Debeya* and narrow leaves of *Magnoliaephyllum* resemble leaves as known from southern Europe and the latter two genera and *Nelumbites* and broad-leaved *Magnoliaephyllum* suggest affinities with North African vegetation.

South Jordanian Cenomanian to Turonian sequences resemble those known from western Egypt and the Sinai. In the region of Wadi Qena of SE Egypt, during the Cenomanian (Atrash Formation) marine influence was more pronounced in the north and fluviatile influence was dominant in the south. Here, the Cenomanian sea covered a somewhat rugged topography of Precambrian basement and Paleozoic sandstones along the Red Sea Hills and formed a shore on their eastern side. A pulse of Upper Cenomanian Sea reached far to the south of Egypt with beds containing *Lingula* and to the east reaching the area of Kharga and Dakhla oasis in the west with some bioturbations produced by crabs in otherwise fluvial deposits. The Upper Cenomanian- Turonian coastal fringe crossed Egypt in a W-E direction from the Bahariya area in the west of Egypt to the southern Wadi Qena area while the Red Sea Hills formed a peninsula. Near the Gulf of Suez the sandy Early Cenomanian deposits consist of a 30-60 m thick sandstone (Malha Formation) composed of coarse sand and gravel deposited by rivers. Some root horizons are evidence for trees which grew on the river deposits at times. The river channels arose at the Red Sea Hill crystalline base in the SW and extended to the NE where their deposits covered the eroded top of Jurassic beds. During Turonian (Tarfa Formation) marine influence in the north of Wadi Qena is documented by limestone beds containig echinids and ammonites, while oyster beds and glauconitic sands are more common in the south.

The Cenomanian–Turonian sequences in Sinai has been differentiated into poorly fossiliferous calcareous sandstones with few bioturbated horizons and bivalve among them many oysters from shallow-sub tidal, calcareous deposits (Raha Formation, middle–late Cenomanian). The boundary between Cenomanian and Turonian has been interpreted to represent a gap of deposition during a low stand of the sea-level. After return of the sea during early Turonian, marl, nodular limestone, shale with some oyster-rich beds and some fossiliferous layers with ammonites, gastropods, bivalves, echinoids, and corals were deposited (Abu Qada Formation). A middle Turonian relative sea-level fall was interpreted to have caused shallow-sub tidal to supra tidal deposition which covered large parts of Sinai with quartz sand and clay mud flats present in south Sinai, similar to the Negev. Upper Turonian is represented by marl, nodular and dolomitic limestone with abundant ammonites (Wata Formation). A hiatus across the Turonian/ Coniacian boundary has been assumed from central Sinai. In Late Coniacian the area was again flooded with a relative sea-level rise.

7. Chalks from the Coniacian to the Eocene in Jordan

In Jordan a sudden change from limestone and marl to chalky sediment occurred at the end of deposition of Wadi Sir Formation and with the begin of Ain Ghazal Formation (Umm Ghudran Formation). Within the Coniacian about 87 Million years ago the minute sceletal remains of a planktonic alga rained to the bottom of the sea and composed here much of the muddy ground. Chalk rich sediments predominates over most of Jordan and in the southeast carbonates grade into fluvial sands and clays. Westward flowing circum-global currents of the Tethys Ocean were probably responsible for a continuous warm climate. In connection with the rotation of the earth, upwelling of deeper water along the south-eastern shores caused exchange of water masses and changed their chemisty. The water of the shelf sea covering most of Jordan thus became quite fertile herewith increasing the growth of a special unicellular algal group, the Coccolithophorida within the Plankton. These coccoliths compose much of the chalk limestone of Ain Ghazal Formation. Similar chalks are common also in other shelf seas of the Tethys Ocean and appeared during Late Cretaceous also, in different locations of seas connected to that Ocean such as in France and England where chalk deposition started even earlier. In Egypt, in contrast, chalk formation began later.

The Late Cretaceous sequence of Belqa Group holds the chalky Ain Ghazal Formationat the base (mostly Coniacian), the Amman Formation with much chert (Santonian and Campanian), the Ruseifa Formation with much phosphatic sand (Campanian), and the chalky-marly Muwaqqar Formation (Maastrichtian) at the top. The equivalent in Israel is the chalky Menuha Formation at the base, Mishash Formation with chert beds and phosphatic layers in the middle, and the dark marly-chalky Ghareb Formation on top. Chalky deposition continued into the Tertiary composing much of the Paleocene and Eocene deposits in Jordan.

During the Coniacian lime production on the Jordanian shelf of the Tethys Ocean switched from predominently benthic organisms as originators to the skeletal parts of predominantly pelagic organisms. Most of these are members of the Plankton with tiny shell such as coccolith and foraminifers (planktic heterohelicids) with small shell. Coccoliths and foraminifera are also part of the carbonate composing the limestones of Cenomanian to Turonian age, but did not provide the predominating materials. These were delivered predominantly by calcareous skeletons of invertebrates and benthic algae, many of which were aragonitic. The skeleton of the Coccolithophorida consists of calcitic elements which are quite resistent to diagenetic changes. Within the cell of this yellow-green algae with only approximately 0.1 mm in diameter the tiny calcite plates, each about 0.008 mm wide are secreted and are arranged to form a hollow sphere. Among the different species of this algae the skeletal elements differ in shape and their morphology is often characteristic to the species. The calcitic elements appear in the drifting cell at a final stage of the life cycle of the planktonic algae during which a resting phase is initiated. During cell growth at about the middle of its life cycle the algae may reproduce and multiply without the calcareous skeleton. At the final stage of life the calcareous particles are secreted in the cell and subsequently it sinks to the bottom of the sea and rests here. The organic cell material may serves as food to this benthic stage of life. Coccolith algae nowadays form plankton blooms in many parts of the oceans except in the cold sea. As consequence to the blooms, large amounts of organic material periodically reache the ground of the sea and may remain here because only a part of the cells will rise again. Due to their production of a carbonate skeleton calcium and CO2 are extracted from the sea water and added to the bottom substrate of the sea. In Late Cretaceous and Paleogene coccolith blooms were a regular feature in the sea that covered the Jordanian shelf.

The lithologic change from detrital carbonate sand of upper Wadi Es Sir Formation to carbonte muds of Ain Ghazal Formation (Umm Ghudran Formation) occurred within the Coniacian that lasted from approximately 89-85 Million years ago. The type locality for Ain Ghazal lies in the southern part of Amman next to the spring of Zerqa River. Wadi Ghudran lies near Irbid in the North of Jordan and here would be the alternative type locality of the formation, with basically the same type of chalky rocks. The carbonate muds provided suitable conditions for a rich benthic fauna, but commonly oxygen was used up in deeper layers developing unoxic conditions. In Northern Jordan Ain Ghazal Formation is about 30 m thick, but it may range from 3 m to 40 m around Irbid and from about 25-30 m around Amman. The chalky beds due to their fine grained consistence and little consolidated nature are rarely exposed. Ain Ghazal Formation has often been eroded and forms land-slides when wet. In central and southern Jordan the chalk is intercalated with sandstones (Tafilah sandstone member intercalated in Mujib Chalk at the base and Dhiban Chalk at the top) and in the SE near Batn el Ghul it may even be totally replaced by sandstones which resemble those of the Kurnub Formation. Along the escarpment between Ras en Naqeb and Batn el Ghul, Ain Ghazal Formation measures 60-80 m in thickness and was described as consisting of bituminous clay-stones, cross-stratified sandstones and dolomite siltstones. In Wadi Mujib the thickness is almost 90 m but the formation there consists of a lower and an upper package of chalk separated by sandstone intercalated with limy material. This Tafilah sandstone is noted to overly oyster beds which formed when the river sands met the chalky sea bed and it was transformed on its surface into a hard-ground on which corals and oysters grew when the sea returned and before deposition of the upper chalk unit. On the Sinai the time equivalent to Ain Ghazal Formation are called Matulla Formation with a basal portion of limestone intercalated with sandstone overlain by chalk. A shoal of oolites formed locally. In Wadi Qena of the Eastern Desert of Egypt no equivalent deposit was developed and the area was land at that time.

Change from chalks in northern Jordan to chalk intercalated with sand deposited by rivers in the center and south, and only to sand in the southeast, document quite clearly that, even though, composed predominantly of the skeletal remains of pelagic organisms the chalk was deposited in a shallow sea that had its shore at times in central Jordan and at others in the south.

The originally rich invertebrate fauna that lived in the sea during the deposition of the chalk of Ain Ghazal Formation has largely disappeared during rock formation. For this two factors of diagenesis are responsible. The dissolution of all aragonitic shells, at first, was then succeeded by strong compaction of the former calcareous mud that still contained lot of water. Some bedding planes have survived this process and display totally flattened relicts of mollusks in the form of brownish crusts. Here, for example, ammonites of which only the sheet-like outline of the shell with the organic siphuncular tube are preserved (Fig. 101). Due to the uniform consistency of the lime mud even the remnants of burrow systems have usually been eradicated. Fish scales and teeth, which are common, are well preserved since their composition is of calcium phosphate. Calcareous shells with originally calcite composition such as those of oysters and the tubes of serpulid worms have also been well preserved. Locally the gryphaeid oyster *Pycnodonte* occurs with left valve, horn-like in shape and right valve forming a flat lid. *Pycnodonte* with its thick calcite shell is probably related to the modern *Amphidonte,* which lives in the open sea of the Pacific, while most other oysters have since retreated into intertidal, estuarine and brackish environments. Silizification during diagenesis has affected the uppermost layers of Ain Ghazal Formation and some cherty beds in northern Jordan contain the ammonite that was determined as *Pseudoschloenbachia* (Desmoceratoidea) of Coniacian age. It has a relatively flat shell with the umbilicus accompanied by short node-like ribs which on the flank splits into smaller simple curving ribs. The sides are flattened. The area next to the siphon carries a keel. This ammonite is often perfectly preserved due to the transformation of its aragonitic shell into a shell of quartz still at a stage of rock formation when the sediment was not compacted. Silizification of the ammonite thus was a relative early process in diagenesis, with the silica transported by the pore water of the substrate. The chalks of Ain Ghazal Formation are rarely seen exposed in natural outcrops and usually form smooth slopes between the upper Wadi Sir limestone and the hard first chert and oyster limestone of Amman Formation in northern Jordan. Further south in Jordan more chert beds appear to have developed in deposits equivalent in age to those of the chalky Ain Ghazal Formation in the North.

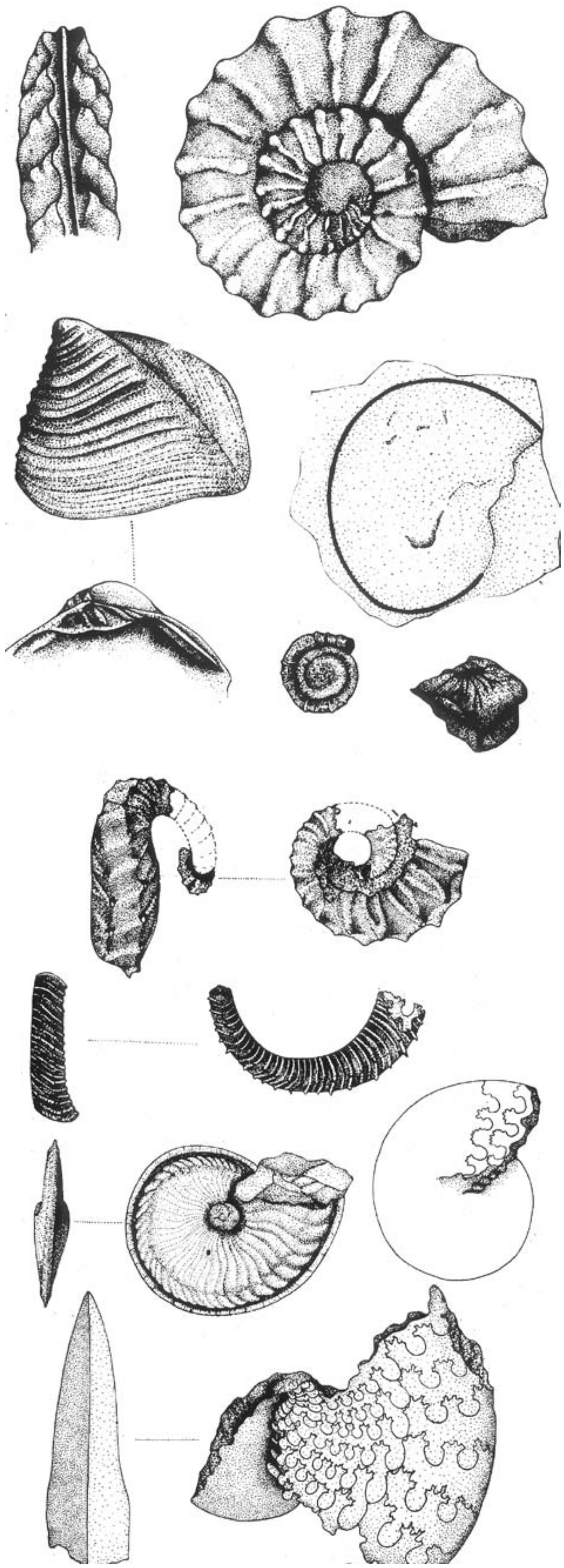

Fig.101: Some fossils from Ain Ghazal, a flattened ammonite with the siphuncle and calcitic worm tube totally preserved.

After the depositon of Ain Ghazal Formation the water covering the Jordanian shelf changes its chemistry somewhat by increased contents of phosphorus and silicium ions. Thus organisms of the Plankton with silicious skeleton such as radiolaria, silicoflagellata and diatoms found good conditions for growth and periodical blooms. This increased the content of silicious shells of the bottom mud and also raised the amount of organic material available. The organisms of phyto-plankton presented the food for the zoo-plankton and the later consisted to a large part of crustaceans as is the case today. Their chitinous skeleton contains phosphorus. Since they were the dominant food for small fish and these for larger fish and marine dinosaurs their product of digestion contained much phosphatic material. Also their skeletal hardpart are composed of calcium-phosphate. Bones and feces eventually dropped to the bottom of the sea and became part of the muddy sediment. Processes within the sea bottom resulted in disssolution of some of that phosphatic material and the migration of calcium-phosphate into fecal pellets and bones within the soft mud. Thus their content of calcium phosphate increased and they crystallized forming hard particles.

Phosphatisation of fecal pellets thus occurred in the soft mud due to interstitial solutions rich in phosphate ions and fixation of these to the organic matter and mucus. When periodical currents washed across the muddy bottom, calcareous shells as well as phosphatized pellets and skeletal particles were winnowed out and enriched in sandy shell beds, which eventually became intercalated with the fine-grained beds. In case such beds were later marginally silizified the delicate originally calcareous shells were transformed into quartz alongside with silizification of phosphatic pellets and bones, documenting that the shells were still present when fecal pellets already transformed into phosphate grains. Aragonitic shells as well as calcitic shells were here silizifieds documenting that dissolution of aragonite occurred cleary later than phosphatization during diagenesis.

Within even thicker columns of sediments at the bottom a migration of silica took place due to the dissolution of amorphous opal of the tiny skeltons of common plankon organisms such as diatoms and silicoflagellates and of the tiny needles of desintegrated sponges. Silica locally replaced carbonate particles and layers tranferring them into chert. These processes, of more or less early diagenesis, are responsible for of the characteristics of Amman Formation, that is the production of phosphatic particles and the growth of layers of chert. The sequence during diagenesis, of phosphatization first, and silizificaton only later, is documented in the occurrence of silizified phosphatic fecal pellets and bones.

Amman Formation has its type section at the cliffs of Ain Ghazal of the city of Amman and is here up to 80 m thick. A 3 m thick chert, chalk and limestone intercaltion forms the base. Characteristic here is a massive limestone bed with oysters belonging to *Nicaisolopha* that resembles modern thick shelled oysters of the genus *Crassostrea* ornamentd by low ribs. It has its umbo only slightly curving to the side. Individuals with both valves in place and usually not cemented to its neighbor are present at Ain Ghazal, while shell debris of oysters represents this layer at Wadi Sir. Laterally this limestone bed is also developed without oysters and, in that case, commonly contains other large bivalves which may also be silizified.

Thick, often continuous chert beds are the most characteristic feature at the base of Amman Formation (Fig. 102). It is found in North Jordan, widely exposed in Wadi el

Gahfer at the western margin of Irbid with up to 60 m in thickness. Its thickness appears to be greatest in the region of Wadi Mujib were 135 m are reported. The southernmost exposures of Late Cretaceous rocks in Ras en Naqab is about 40 m in thicknesss. The thick oyster bank is locally developed throughout Jordan. Only in the outcrops near Batn el Ghoul in SE Jordan, Amman Formation has been reported to consist of red sandstones containing many shark teeth and bone fragments. This resembles sedimentary conditions as encountered in SE Egypt in the Wadi Qena where a bone bed (Abu Had Formation) overlies the Turonian Tarfa sands. Bones and teeth form there locally thick layers in a unit that appears to represent terrestrial deposits in flood plains. Many dinosaurs may have roamed these swamps which probably were strongly vegetated.

The area on the northern margin of the tropical Tethys Ocean lay in the path of the easterly trade winds which could well have created a circulation pattern of warm surface water leading to a coastal upwelling of nutrient rich water from deeper ocean zones. When currents spread the cold or cool water over the shallow broad shelf of the Arabian-Nubian Continent its warm climate warmed the water and rich fauna and flora of planktic and nectic organisms developed. But it is also possible that the water of the rivers carried with them dissolved minerals. A climatic change from drier to more humid conditions came alongside the change from lime to chalk in the deposits of the sea. Productivity of the fertile water of the shelf was so high that organic deposits were not totally decomposed by rich benthic, soft bottom fauna comprising among others molluscs and crustaceans. While the former left their shells in abundance, the larger of the latter excavated their burrow systems now found in profusion. Organic matter can be preserved under conditions of oxygen deficiency such as those which develop in areas of high fertility. If decomposed early enough during diagenesis organic matter can also contribute phosphorous to the interstitial water toward apatite formation. The phosphogenic belt of Late Cretaceous in the southeastern Mediterranean stretches from Marocco to Turkey.

Diatomes are unicellular algae with a pill-box like silicious shell and in part represent members of the phytoplankton, that grows in the ocean in the light of the sun. Others with opal shell are the Radiolaria which live from catching food predominanly consisting of algal cells from the phytoplankton. Often many individuals form larger floats in which they are connected to each other by mucus. The Spumellaria among the Radiolaria have a radial-spherical skeleton and the Nassellaria have a bell shaped conical shell. They cooperate with algae (dinoflagellates) as symbionts. Food is caught by plasma threads (axopodes). Radiolaria change their reproductive mode from sexual to asexual and back, can thus under favorable condition multiply rapidly to exploit blooms of phytoplankton in the water. Their skeleton of opal usually dissolves when it mixes with the carbonate mud and forms the source for chert formation within the sediment and for local replacement of shells by quartz.

Silizification during relatively early diagenesis locally preserved the delicate shells of a fauna that lived in and on the muddy calcareous sediment. It occurrs next to flint nodules and chert layers and connected to their formation. In a narrow zone near the upper and lower surface of some chert layers of Amman and Ruseifa Formations silizification took hold of single shells without selecting a certain skeletal mineralogy. Aragonitic shell for example of juvenile ammonites, calcitic shells of benthic oysters or planktonic foraminifera, shells with mixed composition of organic and calcitic material as that of ostracodes, chitinous material such as crab claws were here transformed into quartz. Transformation locally preserves ultrastructure of shells, for example the crossed lamellar structure present in the shell of a scaphopod or gastropod was conserved with the smallest structural units seen, of 0.002 mm in width.

The preserved fauna represents that of a fully marine environment in the shallow sea with soft bottom substrate. It also documents that the surface of the sediment was usually fully aerated, while within the sediment oxygen was absent, at least at times when solemyid bivalves lived here. They culture sulfur bacteria on their gills but have to breath oxygen, so the live within sediment that is predominently free of oxygen but with oxygenated water above it.

While most muds formed below the wave base, in some layers indications of the intertidal regime such as hardgrounds bored by bivalves and mud sherd layers are also noted. Silicification sometimes also occurred in phosphatic sand and transformed already phosphatized pellets into quartz. Just next to the thin layer of perfect preservation with only a few mm in thickness at the margin of chert, shells are flattened, broken or deformed and a short distance further into the chalk or limestone no trace of them has survived. Within the actual chert beds or flint nodules next to the well preserved shells only indistinct traces of remains are still seen. Here only large and originally thick shells especially when originally of calcitic composition were preserved. In the chalky limestones, and the marly, sometimes strongly bituminous chalks and limestones next to chert layers, fossils were not only destroyed but commonly also a fine lamination appeared, which in most cases was originally not present in the sediment and represents a product of compaction and diagenesis.

Silizified fauna provides very much information about paleoecology and paleobiology of the fauna in case one recognizes its rather special mode of formation in only a very limited zone within the original sediment. Preservation is present in only few and thin layers near to flint beds. This conservation of a formerly almost omnipresent rich fauna also documents the limitations of fossil preservation. Most of the shells of the molluscs encountered consisted of aragonite alongside with little organic material. When shells are enriched to form thin coquinal beds, their sorting is poor and ostracods as well as bivalves commonly have both valves still connected to each-other. Their living place must have been very close by and they moved very little or not at all after their death. These assemblages also contain many shells of veliger larvae of bivalves and gastropods. The original shell rich composition of the sediment is also perserved in such layers, where locally during early diagenesis calcareous concretions formed. Especially, they can document the totally bioturbated and richly fossiliferous composition of the original sediment in the thin sections of these concretions.

Among the silicified small fossils the embryonic shells of ammonites (Ammonitella) are common in some layers. They are ornamented with delicate tubercules and also the interior is preserved including the formerly organic siphuncular tube and the originally aragonitic septae. Such ammonitella is also found attached to juvenile ammonites, especially of those of the genus *Baculites* which represents the most common ammonite here. In its shell the coiled ammonitella is succeeded by an uncoiled, almost straight teleoconch. Baculitidae with *Baculites* lived from late

Turonian to the end of Maastrichtian (approximately 90-65 millon yeas ago) and represent a rather strange group of ammonites. They resemble the early bactritid ancestors of the ammonites in general which lived during Devonian when ammonites began their existence. But *Baculites*, regarding the ammonitella, and the complex suture line formed by the septa with their attachment to the inner shell wall, has the characteristics of modern ammonites. It differs from the ancient anstestors which had simple and unfolded attachment of the septa to the interior of the shell and had their embryonic shell only partly coiled. The mode of life of *Baculites* is still in question. Probably it lived as Nekton partly resting on the bottom, perhaps here collecting prey and partly swimming from one place to the other. Baculitids were extremely common in the shallow sea of Jordan during the Santonian and Campanian and lived here together with several other ammonites with normal and planispirally coiled juvenile shells and also some other species of the Heteromorpha, but the latter were much less common. Heteromorph ammonites deviate from regular planispiral coiling in the construction of the phragmocone added to the ammonitella. Reconstruction of their mode of life gave room to many speculations. Most probably they lived predominantly as free swimming and drifting animals of the plankton and fed from the other members of the zooplankton.

Among the bivalves species of solemyid, nuculid and other palaeotaxodont species, several taxodont (arcoid) and many heterodont lamellibranchs are represented. In many cases their shell was drilled by the carnivorous naticids. *Nucula* as well as *Yoldia*-like species are present with the first burried, shallowly in the bottom mud, the second, deeper down. Both live nowadays on and in soft bottoms by collecting their food by licking deposits from the sediment surface. The *Solemya*-like species often still with both valves attached to each other. They can provide different information regarding the original sediment since they live in muddy bottom with partly anaerobic character. Solemyidae keep contact to the surface to bring into it aerated water, while they pump from the sediment hydrogen-sulfide rich anaerobic water to feed the symbiontic bacteria which they culture in their gill.

Several species of heterodont lamellibranchs are present and most of them lived more or less shallowly buried within the sediment keeping contact to the water above to be able to filter suspended food from it. Small mytilids and arcids lived byssally attached to objects lying on the ground or organisms extending above it such as sponges or algae. The large number of bivalve larval shells which did not continue to grow after settling to the ground is an indication for the special conditions of soft mud here. It obviously was not the right place for them to continue their life after completion of their pelagic larval stage. Pholadid bivalves excavated their home burrows in consolidatd mud beds, some of which were later transformed into chert.

Scaphopoda with their tube like shell that is open on both ends are very numerous in some layers. These molluscs represent carnivorous animals of prey which usually hunt for foraminifera and actively burry through the soft sediment. Their presence in large numbers in some beds indicates the original abundance of prey. Many minute juveniles along with further grown to fully grown large specimen are evidence for life close to their location of preservation. The death of many individuals can commonly be explained when their shell bears a round hole, as is excavated by naticid gastropods in order to reach their prey, as they still do today.

Gastropods represent a mixture of species with quite different ecology. Sometimes naticids predominate, other beds have mostly cerithiid, aporrhaid or ringiculid gastropods. Each of these provides us with a different information in regard to the original sediment and the different preferrence of food. Naticids need a well oxygenized environment in which they hunt their molluscan prey usually by burrying through the sediment. Naticid shells in all size ranges are found, many of them have a hole drilled into it indicating that larger naticids used smaller naticids as food. These carnivorous gastropods fed on other molluscs and their juveniles also hunted ostracods reaching their body through a tiny borehole. In layers with fine silizification even the embryonic shell of naticids that measures only 0.2 mm in diameter retained its original ornament of small tubercles. Shell shape is so well preserved that it can be recognized that the gastropods had a planktotophic larva and ornament changed during transition from larval shell to the shell of the benthic stage (teleoconch). This preservation allows to detect convergence with gastropods with similar adult shell, quite different to the gastropods preserved in the nodular limestone which are not sufficiently well preserved to allow the determination to the species level and often even not to more than stating that it belonges to the class Gastropoda. A similar preservation of minute morphologial differences of the shell is also recognized in case of other gastropods. In this fossil fauna the shape and size of the embryonic shell allow to reconstruct the size of the egg from which it developed and whether or not a larval stage followed. The shape and ornament of the larval shell allows reconstruction of the time the larva spend in the plankton before it settled to benthic life and to which group among the many units of the gastropoda it belonged. Thus, the preservation of the fossils in Amman Formation can provide information of gastropod life and evolution, quite in contrast to the preservation of aragonitic molluscs in formations below and above.

Relatives of *Aporrhais* live on muddy substrate and here burry shallowly in the ground keeping contact to sea water which they filter for food. Their common presence is an indication of the presence of much phytoplankton of seawater. The information is similarly in the case of *Turritella*, which is common in some other layers. They also collected food in a sessile way by burrying shallowly within the sediment and keeping contact to the surface to pump water through their mantle cavity extracting phytoplankton with their gill. Both grew to larger size and can be found on bedding surfaces of chert beds which also documents that in their living environment of the muddy ground of the sea at time of deposition of Amman Foramation they grew to full size. The adults also allow to distingish the species and present evidence for the presence of different species here. Their absence from the sediment next to these surfaces of chert beds is also as indication for the diappearance of even large shells during the following diagensis in case the aragonitic material of their shell was not transformed into silica.

Small cerithiidae are indicators for species which live nowadays on algae or sea grass. Their abundant presence in some layers of Amman Formation indicates that the sea bed was illuminated to allow algae to grow. Opercula of serpulid worms preserved in the silicified fauna, indicate that polychaete worms lived here too, attached to some kind of secondary hardground that has not been preserved, and confirm the interpretation provided by Cerithiidae.

Ringiculid gastropods are members of the cephalaspidean gastropods which hunted small organisms, mainly foraminifers, but also small molluscs and ostracods within the upper sediment layers. Their modern representatives prefer soft bottoms below the shore and below wave base, as is still the case with *Ringicula* in the Gulf of Aqaba. Other cephalaspideans, such as several species of bullomorphs probably fed on algae as is the case among their modern representatives *Bulla* and *Haminoea* in Aqaba. The members of the whole group of Heterostropha can be recognized and distinguished from the other gastropods by the organization of their tiny protoconch that is coiled to the left in the embryo and the larva and coils to the right when changing to live on the bottom of the sea. In such fossils, where this character of usually less than 0.5 mm in size has not been preserved, determination can be difficult or may not even be possible at all. For example the presence of Pyramidellidae which suck blood from worms and mollusk hosts can thus be documented from Amman Formation representing the first species of this rich group known to science and now living in the Gulf of Aqaba.

Some species belonging to the Ctenoglossa were recognized in their relation by the ornament of their larval shell. They tell us, that their host was living here as well. Ctenoglossa of the cerithiopsidean type with characteristic ornament of their larval shell usually parasitize sponges, while those of the Eulimidae with smooth larval shell suck body liquid from different echinoderms.

Several species of Ostracods are preserved with well preserved ornament of their shell and represent the same species that were described from the Mishash Formation as it occurs in the Negev in southern Israel. Silizified pelagic foraminifers are preserved with their delicate shells in such way that they still display the tiny pores which allowed the pseudopodia to reach out into the water to secrete fine spines and to catch food. The ear bones (otoliths) of fish are evidence for the presence of numerous fish and their teeth. Vertebra have also become silizified.

It has sometimes been assumed that life occurred only at certain stages of the deposition of the sediments of Amman Formation and at other times the bottom was oxygen depleted. But this interpretation for most of the beds is not correct. The scarcity of fossils is predominantly due to their disappearance during rock formation. Silizification of some beds occurred after slight compaction occurred, before the minute aragonitic shell remains dissolved. Transformation of fine-grained beds into chert occurred when beds were covered by several meters of sediment. Muds formed due to increased deposition of carbonate skeletal remains of planktonic organisms, while chert formed due to the solution and redeposition of siliceous skeletal elements (sponge spicules, diatom and radiolarian skeletons) in the sediment.

The time and location of silizification can also be studied from the small scale fold-like synsedimentary structures with an amplitude of few meters to wave length of about 5-25 m which occur in many places around Amman. The folds do not continue into the underlying and overlying beds. Most diapiric folds and domes are found in the lower beds of Amman Formation that overlie the chalky Ain Ghazal Formation directly. Water released during diagenesis of the marly chalks pushed up the well bedded mud-sand intercalations of the deposits of the Amman Formation into diapiric mounds. The chert bed in these structures was not fractured and thus their formation was later than the folding of the strata. Thus silizification in the Amman and Ruseifa

Formation occurred deep within the sediment, but at shallower depth than aragonite dissolution and displacment by silica. In the case of fully formed chert beds of Amman formation were folded or fractured they brake into sharp small chert clasts as can be observed in the structural folds that formed during the deposition of Ruseifa Formation just south of Ruseifa (Fig.102).

Fig.102: Chert layer of Amman Formation with clasts

Ruseifa Formation formed in part as result of erosion of deposits of the type as present in Amman Formation. The formerly evenly leveled sea bottom raised locally, sometimes even above sea level due to structural unrest which affected the Jordanien shelf sea in several regions. Such unrest at about the same time with movements of the upper crust in the later Alpine chains is called the “Gosau phase”, and perhaps the “Syrian Arc” movement is connected to it. During the Gosau phase, which received its name from an area in the Northern Alps in eastern Austria, the subsurface of the crust was compressed in such a way that the sedimentary column above detached from it and was folded or even broken. Independent sheets were also piled on top of each other. During about this phase in Jordan the crust was locally undulating along NE-SW lines, which was the result of a stronger push from the African continent towards the Eurasian Continent. At that time the oceanic crust of the Tethys Ocean was still present in the North of the African Continent and Arabia had not begun to separate from it. In Jordan it resulted in local erosion of sediment and its redeposition during which particle washed from them were separated from each other by size and weight. Thus the sediments formed at the time of Amman Formation, especially of phosphatic products of early diagenesis in the muddy sea bottom became locally redeposited, and formed the phosphatic sand in Ruseifa Formation. Such phosphatic sands often formed behind barriers of oyster reefs presenting evidence for their formation in shallow water near the coast (Fig. 103).


Fig. 103: Turtle from phosphate sand near Tel es Sur, south of Ruseifa.

Ruseifa Formation is typically developed in the Ruseifa phosphate pits to the east of Amman with a thickness of about 20 m. Intercalation of carbonate mud and phosphate sand characterize the deposits. The sand came from winnowed and eroded beds of Amman Formation, and the mud was partly deposited in anoxic environment and in part with oxygenated environment in lagoons as well as in the shallow open sea. Differences of former sea-bottom conditions are well conserved in calcareous concretions which formed in these deposits before they were compacted. In the laminated mud of the anoxic lagoon also outside of the concretions bones of fish remained connected. In the well oxygenated mud bivalves gastropods and scaphopods lived and crabs and other burrowers churned the mud (Fig. 104). The concretions which can be very large formed within the limy sediment not only before it was compacted but also before dissolution destroyed aragonitic shells and flattened fecal pellets. But subsequently to concretion growth all aragonitic shells were transformed into calcite. Thus the original fabric of the sediment is preserved in them, but not the original material of the shells.

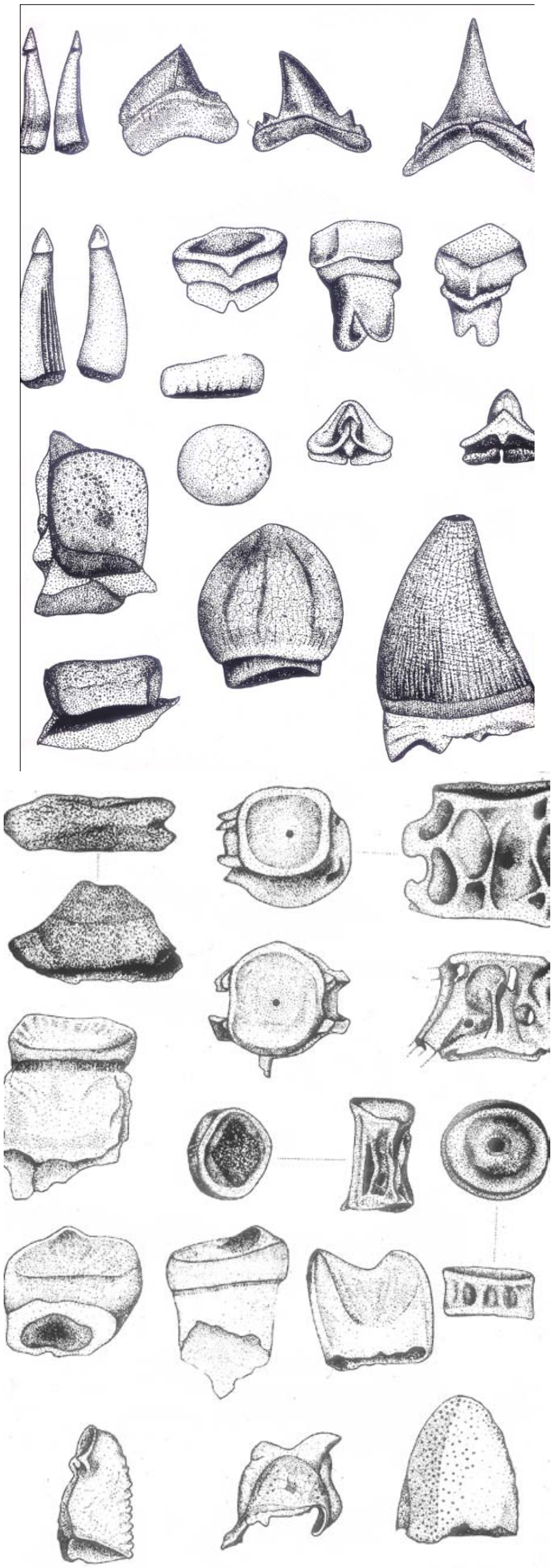

Fig. 104: Phosphate fossils from Amman and Ruseifa Formation. On the right diverse fish teeth and a tooth of a marine reptile in the lower right, on the left vertebra and teeth and in the lower row remains of crabs.

The phosphate sand found at Ruseifa came from nearby and its source can still be well recognized and reconstructed in Tel es Sur region, a few kilometers to the south of Ruseifa Phosphate pits. The four phosphate beds in Ruseifa which were exploited were settled by crabs at their time of deposition. Crab burrows reach into the limestone below and are filled with phosphatic sand. The first about 2 m thick phosphate sand is overlain by clasts of limestone which formed when limy sediment, with and without fauna, fell dry and was dissected by mud cracks, later reworked by the sea. The second phosphate bed lies 2 m above the first one and is a little thinner and has mud pebbles at its base. During the emplacement of the phosphate sand, the muddy sediment was eroded and transformed into mud pebbles. During its deposition thus pebbles of mud were also transported to the same location, documenting the strong current that must have been present. The sand had also been bioturbated by infaunal animals among which crabs which left still recognizable burrows. The sand is covered by marine limestone with fauna including ammonites, especially the slender elongate baculitids. The third phosphate bed with many bones and teeth in it is covered by layers, which in part formed under oxygen free conditions and were not bioturbated, but contain fish skeletons which are still articulated. From the fourth phosphate sand crab burrows extend into the limestone below, but bioturbation did not totally destroy the original large scale cross-bedding of this about 2 m thick bed. The overlying limestones and cherts are intercalated with calcitic debris of oysters. Stromatolitic beds and channels as well as layers composed of former mud balls present evidence for deposition within the intertidal regime.

These four banks composed of coarse phosphate sand had their origin nearby derived from eroded beds of sediments of the Amman Formation which were approximately 25 m thick before erosion. In a series of outcrops to the south of the former Ruseifa phosphate mines the four main phosphate beds can be traced towards the hills of Tell es Sur where they end near the former beach that is well exposed and even displays the former cliffs eroded by waves. When Tell es Sur emerged above sea level, Campanian, Santonian, Coniacian and upper Turonian strata were eroded. Each of them displayed a different stage of rock diagenesis when uncovered by erosion. Shore breccias of chert, and a beach zone with debris of oyster shells are exposed at a cliff (Fig. 105). Oyster reefs grew along this shore and are still preserved with their shells, but, locally these were ground down to form calcareous sand that was deposited on or near the former beach.

The soft Ain Ghazal chalk was eroded off from the hard limestone of uppermost Wadi Sir Formation with the later forming cliffs. Thus the rocks of both formations were of similar composition. The lower beds in the approximately 25 m thick deposits of Amman Formation had chert beds already fully crystallized and hard and when eroded the chert broke into characteristic small angular fragments. These became mixed into the phosphate sands exposed on the slopes of the hills. In the higher deposits of Amman Formation chert had not started to form and fine grained, somewhat consolidated layers, were eroded to form mud balls and mud suspension in sea water. But here fecal pellets had already consolidated by phosphate cements formed within them. These phosphate grains as well as bone fragments and teeth where washed together into sandy layers that can be traced down the slope towards the North to the Ruseifa phosphate mines. Muddy layers deposited on the phosphate sand, in periods with slack water, were later exposed to the atmosphere and mud cracks formed. Afterwards, when a new flood came sand filled the cracks. Mud sherds could also become picked up and deposited nearby in concentrations (intraclast layers).

Fig. 105: Tel Es Sur chert breccia

Thus, in the area of Tel Es Sur, just south of Ruseifa phosphate mines, sea bottom rose above sea level so that a chain of islands formed and sediments of the Amman Formation were eroded and the sand-sized componants in it redeposited in shoal sands in the north. This emergence is connected to the Suweimi-Amman-Ruseifa fault which was active during the time of deposition of the Ruseifa phosphates and along its course the fault continued to be active to our time and thus lies in a series of hills. The fault finds its continuation to the south of the Dead Sea and can be traced on the western side of the rift in modern geomorphology, quite well visible in aerial photographic documentations with more than 100 km displacement along the transform fault.

Local sliding, and synsedimentary folding occurred in the sediments deposited on the slope of the island chain. A synsedimentary fold exposed near Tel es Sur documents that silicification occurred deeper than 10 m in the sediment. Beds lying in several meters deep within the sediments of Amman Formation were not silizified, thus no chert was presents but phosphate particles of sand size formed within them. A small quarry exposes the phosphate sand very well since here at Roman times perhaps 2000 years ago columns were produced and not all of them carried away at a time when the houses of their city Philadelphia were constructed at the place that is now Amman)Fig. 106). These beds also contain the teeth of dinosaurs and sharks and reptilian bones. The remains of a large marine turtle is preserved next to half finished columns carved from the hard phosphate. In contrast to the phosphate sands at Ruseifa here also fine fragments of chert are found mixed with the phosphate sand documenting that chert layers were also eroded nearby. In the outcrop at Tel es Sur evidence is conclusive that layers of predominantly muddy sediment of Amman Formation were transformed into chert and that, that occurred under a cover of at least 10 m of overburden.

Fig. 106: Tel es Sur with the Roman quarry in front with half-finished column of hard phosphate, an intraformational fold in Amman Formation below the lower road and the remnants of an oyster reef on the top of the hill behind the tents belonging to the beach deposits of Ruseifa Formation.

The Campanian Ruseifa Formation in Amman is called Al Hisa Formation in central and southern Jordan. Here it is also a heterogeneous unit and consists of chert, marl, phosphates, and oyster-rich limestone. Most of the phosphate consists of pellets, fish teeth and bone fragments. At Al Hisa large oyster reefs and accumulations up to 30 m thick composed of *Ambigostrea* with many radial ribs and *Oscillopha* of the Palaeolophidae with foliated shell structure are connected to the phosphate deposits. Faults running roughly NE - SW are connected to the phosphate beds also in other areas than that of Ruseifa, for example in Al Hasa. In the area of Wadi Mujib, Amman Formation is very thick and Ruseifa Formation can not be distinguished from it. Here obviously sedimentation in the sea continued while to the north and south the former sea bottom, locally became exposed to erosion. In the North of Jordan in Irbid, Ruseifa Formation may measure 12-16 m in Wadi Hofa with thick phosphate beds, and not far away in Wadi Gahfer it is not developed at all. The depositional area locally varied much so that the thickness and the lithology of the deposits of Amman and Ruseifa Formations are very variable.

During Maastrichtian the Tethys Ocean periodically flooded much of the African continental plate. This is when Muwaqqar Formation was deposited in Jordan which is characterized by the disappearance of phosphate beds and chert, as well as the appearance of massive marl and chalky marl instead, with transition well exposed in Wadi Arda west of Salt (Fig. 107). Here in its basal portion, phosphatic grains decrease in abundance and some harder beds of limestone are intercalated that laterally may change into layers of concretions. Ammonites occur and planktic foraminifera document well that the sequence here goes to highest Maastrichtian, without any hiatus of sedimentation. This is different in about 20 km to the east of Irbid in Wadi Shallale where such a hiatus is present and deposits of the uppermost

Maastrichtian are missing, as well as those of the lowermost Paleocene. The indistinct hardground developed here is settled with oysters, which sometimes used winnowed concretions as place for their attachment.

Fig. 107: Muwaqqar Formation in Wadi Arda in northern Jordan

Fig. 108: Transition from Cretaceous to Tertiary in Wadi Arda. The boundary lies in the upper part of the small valley above the hard layer on the dry waterfall.

The thickness of Muwaqqar Formation differs considerably, and it appears to be thickest in Azraq trough and also in Jafr Basin south of that, while it is missing to the East of Azraq. Near Irbid it measures over 100 m. Locally the beds of Muwaqqar Formation contain a high bitumen content probably formed in basins in which bottom substrate was low in oxygen, while the sea had a high plankton production. Here organic material did not decompose and “oil shales” developed.

In SE Egypt St. Paul Formation overlies Cenomanian deposits (Atrash Formation) in the Galala Hills and the Campanian Abu Had Formation to the west of Wadi Qena and consists of chalky beds with a thickness of 90 m. These white chalks are exposed over a large area to the west of the area of St Paul monastery. It is possible that these chalks are time equivalent to the Muwaqqar in Jordan. At the northern escarpment of the southern Galala hills the chalk is overlain by 190 m of chalky limestone, marl and sandstone and contains Maastrichtian ammonites and an Exogyra found in western Egypt and further in the Sand Sea. The transition to the Tertiary is always connected to a hiatus (Fig. 108).

The impact of a meteorite into shallow waters of the Tethys near modern Mexico at the change from Mesozoic to Cenozoic time seems not to have strongly visible influence on sedimentation in Jordan.

11. Paleogene of Jordan

Transition from Cretaceous to Tertiary in the deposits of Jordan is indistinct. Neither the type of sediments as bituminous chalks nor the visible fossil content predominantly seen as burrow systems in that chalk change, and the disappearance of ammonites due to their becoming extinct is also not evident because they are rare in the sediments of Muwaqqar Formation. Only when micro-fauna is extracted from the chalky sediment the change from Cretaceous to Tertiary is clearly documented with the planktonic foraminifera belonging to the genera *Globorotalia* and *Subbotina* which are related to modern *Globigerina* repreesneted by different species and distinct species also define the different stages of the Paleocene and Eocene.

The Tethys Ocean closed during Paleogene (Paleocene to Oligocene) due to subduction of its oceanic crust which resulted in mountain building (orogenies) such as those of the Alps and Taurus in contact to the African-Arabian Continent. For about 30 Million years during Paleocene and most of Eocene most of Jordan remained below sea surface and relatively far from land except for the SE and S where water was shallow so that nummulites found light on the bottom of the sea. To the east of the beach lay the African-Arabian Gondwana.

It was suggested that during the crustal evolution to the East of Oman the proto-Carlsberg spreading ridge between Madagascar and India migrated several hundred kilometers northward during early Paleocene so that India separated and moved relatively to the North. The continental mass of India came close to the new spreading axis which caused the outpouring of lava in Deccan Traps. India continued its rapid (15-25 cm per year) approach towards Eurasia until the first continental collision in the Eocene at about 53 million years ago took place.

During the Eocene, the area occupied by the Mediterranean Sea was still connected with the deep water in the Indian-Pacific Ocean that laid between India and the Arabian-African Continent. This late Eocene Ocean extended to the west connecting with the Mid-Atlantic and further to the Pacific about 35 Million years ago. During mid Eocene a large volcanic zone developed in NE Africa now the Ethiopian highlands. During Lutetian of Eocene the Alpine orogeny was well underway and the crustal shortening during this process also influenced the sedimentary basins of the Arabian platform.

A hiatus usually marks the transition from latest Cretaceous deposits to the earliest sediments of Paleogene. At Wadi al-Arab west of Irbid, in the NW of Jordan the dark chalky deposits of the Muwaqqar Formation of the Maastrichtian continue into the dark chalky deposits of the early Paleocene, Taqya Formation (called Umm Rijam Formation in the south of Jordan). Transition is here inconspicuous and within normally bioturbated chalks of the same facies as in the Maastrichtian Muwaqqar Formation below. The Paleocene has a concretion layer in its lower part, and further above (after about 15 m) a yellow bed of about 5 m in thickness was deposited already well in the Paleogene. In it umbrella-like burrow structures are preserved, consisting of vertical tube that can be up to 1 m long with horizonal branches up to 50 cm long following original bedding surfaces. The upper surface of this yellowish bed is penetrated by numerous crab burrows which reach down to about 20 cm (Fig. 109). As body fossils, sponges occur in the yellow bed and above bituminous chalks follow. The change from the dark marl into the typical white Eocene chalk of Shallala Formation is here difficult to see due to slumping of slopes. The type locality for Umm Rijam Formation is Jabel Umm Rijam inTafila region in southern Jordan, and since preservation of these deposits is very variable at different places in Jordan, it is a bit difficult to compare them with each other and correlate their age with the chalky deposits of the Pleogene in the north.

Fig. 109: The yellow bed at Wadi Shallala representing the base of Eocene.

At the base of Wadi Shallala east of Irbid oysters settled on the hard surface of the erosional uppermost Maastrichtian in the early Paleocene Taqya Formation, preserved on and in concretions. Here in Wadi Shelalla the transition from Cretaceous into Paleocene lies within the same facies of more or less bituminous chalk with big concretions, one of which preserves a narrow and local bed with oysters. Paleocene is here not very extended, and in the first 1.5 m in Muwaqqar facies the bioturbated chalk ends in a more solid bank overlain by bituminous marl. Here, again chalk and a thin marly bed forms the base of the yellow massive bed, with a characteristic lithology and bioturbation as in Wadi al-Arab but without sponges and it forms the change from Cretaceous to Paleocene. The characteristic trace fossil consists of a vertical tube connected to star-like horizontal mining burrows, which were flattened due to compaction. The yellow bed is overlain by marly chalk and this bed is the top of the Paleocene as determined by its content of pelagic foraminifers. It is overlain by white chalk with flint beds of the Eocene Shallala Formation (Fig. 110).

Fig. 110: Wadi Shallala with Eocene chalks above the yellow bed at the right and with tunnels belonging to the former Roman aqueduct to the cities of the Decapolis Abila and Gadara seen in the upper left.

The dark Taqya Formation of Paleocene is succeeded by the white Shallala Formation (Sara Chalk Formation) and both are well exposed in Wadi Yarmouk just east of Hemma. Here their thickness increases from about 250 m east of Irbid to about 350 m in the Yarmouk valley. It contains relatively charcteristic chert and flint beds with the color of the silicious beds usually reddish brown.

Open pelagic conditions are the environment for one of the common Foraminifera of Eocene deposits in most of Jordan represented by relatives of *Globigerina*, while a well illuminated bottom substrate is that of *Nummulites* representing the other characteristic one. Both live together with symbiontic green algae and with their walls composed of calcite. The chambers are arranged next to each other, commonly in spiral arrangement, but with few in the case of *Globigerina* and many in the case of *Nummulites*. During their life cycle most foraminifers have vegetative and sexual reproduction succeeding each other, and that can be recognized on the size of the first initial chamber. A characteristic nummulitic limestone is found at the entrance to Wadi Gharandal in southern Wadi Araba. In the Negev even small coral reefs were reported from the Eocene. *Nummulites* with quite a number of species characterize the Mediterranean Eocene that is the marginal deposits of the tropical Tethys Ocean during that period of time. They are well known from their occurrence in the rocks which were used to construct the Egyptian pyramids and they received their name from the shape of some of them which resemble a coin (Latin nummus). They represent large foraminifers with a heavy skeleton and were living on the sea-bottom in illuminated environment. Their presence in Wadi Gharandal documents deposition in the shallow warm sea in the Bartonian stage of the Eocene around 40 million years ago.

Shallala Formation is also locally preserved in NE Jordan, with marine fossils including bones of early wales, teeth from sharks and sea urchins. The latter among them also of the flat *Echinolampas* type with thick walls were even interpreted to be of younger than of Eocene age.

To the southeast of Jordan on the Egyptian side of the Gulf of Suez in the Galala hills the Cretaceous sediments are overlain by 300-400 m of predominately carbonate sediments. The Tertiary sea extended far onto the African continent reaching northern Sudan. Little deposition occurred during Paleocene, more during Eocene with a transition to shallow water and saline deposits in mid Eocene. Nummulitic limestone covered much of Egypt, including Sinai during mid-Eocene, , which can be connected to the occurrence in SW Jordan at Wadi Gharandal.

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8. Marine post Tethys Tertiary to Pleistocene of Jordan

With the closure of the circum-equatorial Tethys Ocean between Africa-Arabia and Europe, the Mediterranean Sea formed and the oceanic crust existing North of Arabia was subducted. The continental slope of Arabia with the former Tethys off the Levantine shore remained as the same passive margin also to the basin of the Eastern Mediterranean Sea. At about the time of change from Eocene to Oligocene about 35 Million years ago the deep ocean floor between Arabia and Asia disappeared as a result of the collision of the African plate with the Eurasian plate. Subduction of the oceanic crust caused the alpine orogeny by shortening the crust in the collision zone with folding and overthrusting. Seaways which connected the Pacific and Atlantic Oceans had then to pass over some continental crust. The collision of continental plates also resulted in the opening of the Red Sea and the shearing along the fissure in the continental crust that produced the Jordan -Dead Sea- Wadi Araba- Gulf of Aqaba graben and its horizontal displacement zone.

Earliest rifting along the margins flanking the Gulf of Aden spread into the area of the later Red Sea separating Africa from Arabia. In the area later occupied by the Red Sea the crust lifted dome-like and a graben broke in along its central axis. Rifting, and the begin of the formation of oceanic crust in the Red Sea graben is interpreted to have started during mid-Oligocene time about 30 Million years ago. The spreading zone of the Red Sea extended into the rift that continues into the Gulf of Aqaba and the Dead Sea-Jordan rift. The boundary along the Red Sea and the Suez rift formed by the end of Oligocene. Motion along the Dead Sea transform is thus connected to the formation of the Red Sea rift. While the former slope of Arabia to the Tethys Ocean remained as the slope to the deep eastern Mediterranean Sea, a strike slip fault transported the eastern side of the Jordan rift more than 100 km to the north in relation to the western side of that rift. That motion along the transform fault has continued since the Oligocene and is still going on as can be studied on the eastern side of Wadi Araba, where small dry creeks are being displaced along that fault. Here not only vertical displacment produced a small step from higher in the east and lower in the west, but also the creek beds are bent with a twists to the south. The eastern rim of the Jordan-Dead Sea rift represents a major structural feature that extends from the southern tip of Sinai Peninsula in the south to Turkey in the north. Along this Dead Sea Rift horizontal movements of about 110 km and vertical movements of over 10 km have occurred and are still active as is documented by relatively common earth quakes. This movement, if it were continuous, would be 3-4 mm in a year of Arabia against the Levantine. Steep slopes from the Jordanian highlands to the Wadi Araba, Dead Sea and Jordan valley document that structural activity also is also present in vertical direction.

The Dead Sea Transform is a still active plate boundary between the Arabian and the Sinai plates probably continuously since Late OligoceThe relative vertical movement of the rifted areas to the bottom of the down faulted areas along the Rift valley is about 10 km and the rift margins relative uplift to the surroundings (filled rift) is about 1.5 km. Earth quakes along these structural boundaries occur relatively commonly and they have destroyed several ancient cities such as the town Gerasa at the place which is now Jerash and other historical sites in Jordan.

With the closure of the Tethys Ocean between Africa and Eurasia during late Eocene the shelf sea withdrew from the region and Jordan became land. The regression during late Eocene from Jordan and neighboring areas left a flat land which also began to rise but with little erosion at first and with the coast along the Levantine margin to the newly formed Mediterranean Sea.
During Early Oligocene the area parallel to the Jordan-Araba axis was up-lifted before the rift valley broke into that area. River began to transport material from higher regions in the East of the area to northern Jordan and locally further to the west towards the basin of the Mediterranean Sea. A low energy regional fluvial system has been reconstructed in which fine clastic sediments from an area located east or southeast of the Rift valley were transported to the central Negev area. Accordingly, rivers transported flint that was eroded in the area of Jordan to southern Israel, and the Sinai. From about 35 Million years ago in the Eocene to almost 10 Million years later little is known about Jordan, with the exception that it was land and that erosion occurred in an area with little relief.

About 28 Million years ago during late Oligocene the sea advanced from the area of the Persian Gulf and flooded parts of north-east Jordan and reached the depression that formed along the early Jordan Rift, in its northern region, in Lake Tiberias area and south to around the towns Mashara-Abu Habil. Deposits of shallow sea and coastline are found in the depression that formed in the early Jordan rift valley. This transgression of the Pacific Ocean can be connected to a world wide rise in sea level in late Oligocene time, followed by a regression in Miocene about 15 Million years ago. Coastal deposits of this sea became preserved on the eastern slope of the Rift valley for about 30 km from the towns Shuna in the North to Waqqas in the South and less conspicuously to the east of Mashara near ancient Pella. Similar deposits have also been described from the slope of the Golan height to Lake Tiberias not far north of Wadi Yarmouk. At that time, much material eroded from the rising mountains in the east became deposited in the sinking rift valley exposed to the west of Abu Habil in the Al Qarn hills and especially well at their southern margin in the Wadi al Qarn to almost its end in the Jordan River. Less well dated sediments that may belong to the same time intervall are exposed at the begin of the slope next to the road from the Dead Sea and Jericho to Amman and south of the mouth of Wadi Hisban to the Jordan Valley. Here sediments are predominated by sandy carbonate. Of similar age my be the conglomatic beds exposed at the basal slope of the area of wadi Dana to wadi Gharandal in wadi Araba (Dana Conglomerates). They may belong to that early sedimentation into a rapidly forming depression. Near Petra at Jebel Harun this conglomerate has been described as about 120 m thick.

The depression of the Jordan rift was thus connected by a seaway that crossed northern Jordan about parallel to the modern Yarmouk valley and represented a side branch of the sea strait formed by the precursor of the Persian Gulf and in contact with the Indo-Pacific Ocean. This seaway was also connected to a large depression that formed on the continental side of the Alpine fold-belt and the large continental sea of the Paratethys. The northern part of the Jordan Rift was inundated, and the Tayba Formation (Taiyiba Beds) was deposited. In the Jordan valley at Al Qarn hills the exact time of sedimentation is documented predominantly by foraminifers which indicate latest Oligocene and early Miocene age. At Waqqas and North Shuna (Ash Shuna) also some mollusks, sea-urchins and skeletal remains of other marine organisms confirm that age.

In the town of Ash Shuna at the northern slope of Wadi al Arab Eocene chalk with flint beds (Shallala Formation) are overlain by sandstone and limy sandstone locally with concentrations of bryozoans and coralline algae. Other layers bear *Pecten* shells belonging to several species and oysters. Heterodont bivalves are preserved but only as molds formed by sediment fills (steinkerns) as well as elongate gastropods most likely of a species of *Turritella*. Better preserved are originally calcitic tubes of worms and sea urchins of *Clypeaster* and *Echinolampas*. The former beach and shallow water deposits were deformed to form nearly vertical beds along with the Eocene chalk below them at the eastern margin of the rift valley.

Near the small town Waqqas, a well exposed section of Oligocene to Miocene near shore sedimentation of Tayba Formation is developed in the lower slope of the Jordan Rift. The sediments of the section document the arrival of the sea. Beach deposits, and near shore sands each with their characteristic fauna and the transition of sedimentation from normal marine water to that in more saline environment are exposed. Deposits are inclined with about 35° towards the Rift Valley and were transected by faults parallel to the rift margin with about 45° dip. Eroded Paleogene marl and limestone is covered by quartz-rich coarse sandstone bearing more or less carbonate and containing layers with green glaucony. The beach sand that differs in thickness at different localities was thus deposited on bare rock along a rocky coast. The rounded and angular pebbles found in the sands have obviously been derived from the chalky coastline. The sand is strongly bioturbated and in it the best preserved burrows were constructed by crabs which sometimes inmurated the walls of their tunnel systems with feacal pellets as is the case of the *Thalassinoides* type. Above follows nodular limestone that was intensively bioturbated. It contains many fossils of which the most conspicuous are the shells of pectinid bivalves, oysters and sea urchins, all of which may be large and had a thick calcitic shell. More limy beds hold small brachiopods, spines of regular sea urchins, calcareous sponges, octocorals, coralline algae, large foraminifers and bryozoa. Even though aragonitic shells are usually dissolved, casts and fillings of gastropods may be preserved as are larger heterodont bivalves and crust forming corals. Among the gastropods species of *Turritella*, *Ficus*, *Cassidaria/ Galeodea*, *Natica*, *Strombus*, *Xenophora* can be recognized. The remains of stony corals have the bore holes of the bivalve *Lithophaga*. It drills typical even club-like homes into hard calcareous substrate. The smooth walled cavities were later filled with cemented sediment. While the aragonitic skeleton of the coral is usually dissolved, the fill structure remains. The occurrence of bore holes, respectively their fillings, can be used to evaluate water depth, since *Lithophaga* usually drills along the tidal line or just below it. Among the other bivalves, members of cardiids which, when preserved as mold, are recognized by the imprints left of their hinge teeth of different size, fit into a few grooves on the other valve. Sea urchins of the type of *Echinolampas* are found in Oligocene and Miocene of the Mediterranean bio-province occur.

The basal sand in the section at Waqqas is 4-6 m thick and is succeeded by nodular limestone of about 6 m in thickness. These are succeeded by 8 m of sandy, gravel bearing beds with layers with crab burrows. That is covered by beds which indicate that during Early Miocene the water in the sea that filled the Jordan Rift zone increased in it salinity. 5 m of gravel and stromatolitic limestone layers end in a cellular dolomite. Such rocks form when salt is leached out from deposits of salt, gypsum and limestone intercalated with each other. From these near-shore deposits it can be concluded, that further in the rift depression water became saline and perhaps salt deposits formed. It is unknown how much salt of the thick sequences of salt found in the subsurface of the Jordan Rift arrived here with water coming from the Pacific Ocean and how much arrived here later, probably after the Messinian crisis of the Mediterranean from the Atlantic Ocean.

A similar transition from shallow water sand to stromatolitic limestone probably formed in a lagoon is exposed next to the small road to Tayba (may also be transferred in the spelling Attybeh), just a few km south of Waqqas and higher up on the slope and it is overlain by fluviatile pebbles with red soil intercalated. The glauconitic lower layer is exposed for more than 150 m. Between these sand and the Paleogene limestone below no soil is preserved. The marine deposits of 3.5 to 15 m in thickness contain fauna of bryozoans, oysters, brachiopods, calcareous sponges, regular sea urchins intercalated with bioturbated glauconitic sandstone with *Pecten* are found overlain by stromatolitic limestones and these by gravel with intercalated red soil. The conglomerate consists of pebbles of chalky limestone and brown flint as from Eocene, closely resembling the river bed conglomerate at Awsara. This sequence is good evidence for the sea that washed the slope with normal sea water. That latter turned into saline brine with stromatolitic and saline lagoon deposition and was succeeded by terrestrial deposits. The top is formed by conglomerate and the whole sequence dips with about 35° to the west toward the rift.

Coralline or red algae (Rhodophyta) are easily recognized in the consolidated bed by forming white irregularly rounded pebbles with smooth surface of fracture. Coralline algae were living in about the same environment of the turbulent well illuminated sea water since early Cambrian. Their cells have red or violet chromatophores and thus represent the red algae. Those producing calcareous skeletons are often well preserved since they deposit their calcareous walls predominantly in the modification of calcite. In reefs, they form an important part of the core with their rigidity and their ability to withstand the destructive action of the waves. But they also grow just below the beach often forming irregularly rounded growth forms called rhodoliths. Coralline algae resembling *Lithothamnium* can be observed in the Gulf of Aqaba to grow on all surfaces, especially those of dead corals. In the exposures near Waqqas coralline algae are recognized by their irregular shape (rhodoliths) and the fine smooth appearance in fracture, which only in thin section reveals its cellular construction. They occur scattered within the sandstone documenting the closeness of the shore during their deposition.

Pecten and related genera have very good preservation potential because the outer layer of their shell consists of calcite deposited as thin lamina on top of each other and with very little organic material around and within them. Their valves are usually solidly built and often have radial ribs as ornament. Even when broken, their shells can be recognized. On either sides of the umbo and hinge ear-like extensions are present of which near the smaller a gap for the byssus is developed. The hinge has no teeth and on the inner side of the shell the scar of only one of the shell muscles is present because it was much larger than the other. *Amussiopecten* has a large concave valve as the one resting on the substrate and an almost flat valve forming the top. *Aequipecten* is similar in shape and size but has stronger radial ribs and both valves are almost equally shaped.

Pecten of Tayba Formation represents a facultative mobile, epifaunal suspension feeder and was able to escape from a predator by swimming away. The mantle margin extends into tentacles which prevented larger particles to enter the pallial cavity that holds the gills. When a starfish in its search for food approaches *Pecten* it rapidly closes the valves by contraction of is large shell muscle. At the same time the mantle margin covers the shell gape so that water is expelled only along the wings of the hinge. The bivalve is thus propelled above the sediment and repeated shell closures keep it swimming. Shell valves open, after muscle contraction and the following relaxation, due to the solid elastic ligament which connects the valves to each other in the middle of the hinge. At the end of escape, *Pecten* sinks to sea bottom, and the rounded larger valve lies at the sea bottom. All species of *Pecten* have byssus which may be secreted by the foot and with which they can attach to hard substrates. The large individuals that rest on the sea bottom use byssus only when young. Byssus can be detached rapidly when a small or young *Pecten* is attacked. The habits of Pectinidae can well be observed in Aqaba, and here individuals are usually present in the aquarium. They also display mantle tentacles which are somewhat unusual by bearing eyes.

While *Pecten* lived free on the sand, the oysters lived attached. Often their valves are still connected as they occur in the lower sandstone bed within the lower portion of the section of Waqqas and also in the outcrops near the small road uphill from Waqqas to Tayba. By the time of Oligocene-Miocene most oysters had adopted to live in the marginal marine environment. Oysters were able to live and grow in the shore environment and within brackish lagoons. This change from the open shallow marine environment which they preferred in Cretaceous time is due to reactions to predating gastropods, especially the appearance of shell boring Muricidae among the Neogastropoda since the onset of Tertiary. While the carnivorous gastropods avoid brackish water, oysters can live in it and tolerate fresh water for quite some time.

Galeodea and *Cassidaria* are Latrogastropoda of the Cassoidea which have many species that live from echinoderms. In the case of the individuals of Waqqas, their aragonitic shell is usually not preserved but shell shape is so characteristic that they can be determined even in steinkern-preservation. The species of the Cassoidea may have hunted sea-urchins like *Echinolampas*. *Natica*-like shell shapes are less characteristic but their activity during search for food has left characteristic traces. They usually drill a hole into the shell of bivalves or another gastropod to reach their body and eat it by extending their mouth through the hole. *Strombus* has a shell recognized well in case the shell is fully grown. Many species are quite large and the outer lip of their shell is expanded in a characteristic way. Representatives of all three groups can be studied well at Aqaba, and here it is also revealed that *Strombus* feeds exclusively on algae, which also represents the food of *Xenophora*. That latter distant relative of the Strombidae has a conical shell that could easily be mistaken for another gastropod, but as characteristic feature it includes other objects into its shell, such as pebbles or other shells. Thus even in bad preservation the shell of species of this genus can be recognized and was found in Waqqas.

Irregular sea urchins of the *Echinolampas* type (Cassidulidae) belong to a group that entered the sediment and thus evolved short spines which cover the corona like a pelt. They have a low corona with round diameter in contrast to the heart-urchins as are common in late Cretaceous. In Aqaba a similar but even flatter irregular sea urchin is represented by the sand dollar and it has the top and base walls of the corona supported by internal pillars. Like *Echinolampas*, it buries into the sand and collects food from the interstices of the loose sediment transporting particles to the mouth with short ambulacral feet.

Within the depression of the Jordan rift a thicker sequence of sediments became deposited than near the beach and shallow coastal sea as preserved in the outcrops extending from North Shuna to Waqqas. Further to the south, in Wadi al Qarn from just west of King Abdalla Canal to almost the Jordan River south of Abu Habil and just south of the hills of Al Qarn 150 to 200 m of sandy-silty well bedded sediments with conglomeratic top layers are exposed. They are inclined, and deformed near faults forming complex fold structures so that their exposed and original thickness is difficult to evaluate. Into the depositional environment in the depression formed by the rift, rivers coming from the east deposited sand and gravel. An ancient river bed that may be the one of those along which these pebbles were transported is well exposed to the west of the small town Awsara just to the north of Ajlun Dome and east of the Jordan Rift but still in its margin (a few km east of Deir Abu Said, and NE of Al Qarn hills) so that beds were deformed. The sequence in Wadi al Qarn is effected by strong tectonic deformation due to their situation next to marginal faults of the rift valley. Conglomerates form especially extensive layers in the top of the section. They consist of limestone gravel and large pebbles which are usually well rounded and by chert of more or less angular outline. The characteristic flints in these deposits present evidence that during this process erosion uncovered continuously older beds from Paleogene age to late Cretaceous age. The latter may bear some ammonites (*Baculites*) as good indicators of their original stratigraphic position in Amman Formation.

In the section small and large channels are intercalated with reddish silty-sandy beds. Strata may be finely laminated horizontally or as cross laminar. Bioturbation by a number of different organisms produced fine burrow structures as well as larger ones. The latter are usually represented by the characteristic network produced by thalassinoid crabs. This bioturbation is evidence of marine conditions during the deposition of the sediments of the whole section. Layers with mud-cracks and mud sherds formed during dessication are evidence for shallow intertidal conditions (Fig. 111). Fine laminar bedding might have formed under the influence of algal or cyanobacterial crusts. Rippled sediment surfaces are also preserved and exposed in Wadi al Qarn. Synsedimentary fracturing of already deposited beds can be considered as having formed during structural unrest, for example during earthquakes. Slumps also occur. In the central part of the section some chalky layers contain a fauna with benthic foraminifera of species of the genera *Cibicides*, *Hanzawaia*, *Dentalina*, *Uvigerina* and *Heterolepa* which indicate Oligocene to Miocene age in addtion to species of the planktonic Foraminifera of *Globigerina* and *Tenuitellinata* which are characteristic to Oligocene (Fig. 112).

Fig.111: Laminated, mud cracked and bioturbated layers of limy clay from Tayba Formation at Wadi al Qarn document their deposition in very shallow sea and on mud flats.

Fig.112: Tayba Formation exposed in the southern slope of Wadi al Qarn with white chalky beds containing planktonic foraminifera of Late Oligocene age. The person on the slope is Rafie Shinaq.

Foraminifera are unicellular organisms which move and feed with pseudopodia consisting of structured protoplasma. With these "feet" they collect and take hold of organic particle and small organisms such as diatoms. These are surrounded by plasma forming minute digestive system within the blister. In its interior the food is digested and afterwards the blister opens and the protoplasma is withdrawn. C*ibicides* has a low trochispiral calcareous and thick test consisting of seven to nine chambers with the last chamber rounded. The test in cross section is plane-convex with rounded walls. Chambers increase gradually in size and have perforations on both sides of the test. The aperture of the last chamber is a narrow slit bordered by a thin lip. *Hanzawaia* has a similar shape of the test but the aperture of the last chamber lies on the outer margin. *Heterolepa* also with spiral arrangement of the chambers has the pores on both convex sides and the aperture as inclined slit on the inner side of the last chamber. *Dentalina* is elongated with the chambers increasing in size and forming a row and the last chamber with an aperture surrounded by a collar. The chamber walls consist of calcite. *Uvigerina* is composed of chambers increasing in size in alternating row and with axial ribs and a collar around the final aperture. The composition of its walls is of fibrous calcite. The pelagic Foraminifera *Globigerina* differs from *Tenuitellinata* by possessing a macro perforate, rather than a micro perforate test by having a different aperture. The test consists of calcite with many pores in the wall and the pores larger than in benthic species. These Foraminifera swim in the sea, drifting in the Plankton by reducing their weight by small drops of oil that is lighter than water in their cell.

Lepidocyclina represents a large disc shaped foraminifer found in the beach deposits of Tayba Formation. Very similar large foraminifers live nowadays in the Gulf of Aqaba and climb onto blades of the sea grass or onto the surface of rocks in the shallow lagoon to catch the light of the of the sun, because in their tissue, algae as symbionts help them to breath and feed.

At the base of the slope and next to the mouth of Wadi Hisban into the plain of the Dead Sea a chain of small mountains composed of sandstones with their strata strongly tilted bear bedding surfaces with current marks on their top and loading structures on their base. These rocks may be part of the Oligocene -Miocene marine deposition within the Jordan Rift, but they still need to be dated with fossils. Further south between Wadi Dana and west of Shobak and Wadi Gharandal, Dana Formation is a sequence of conglomerates and sand- silt deposits of about 250 m in thickness. It may also represent a part of the same depositional history as Tayba Formation. This sequence provided no conclusive fossils, but crab burrows are recognized. On the Mediterranean side of NE Sinai an upper Oligocene sequence consisting of sandy limestone with many coralline algae was noted with similar composition to the calcareous bed in Waqqas section. But this had been marginal to the Mediterranean Sea.

Pollen from clay of Oligocene to Miocene age were analyzed and document that a flora of warm, dry subtropical character with Juglandaceae (*Juglans*, *Pterocarya*), Betulaceae (*Alnus*, *Corylus*, *Caprinus*) and Pinaceae was living in the area.

The closure of the extention of the Persian Gulf to the Mediterranean and to the sea in the Paratethys Basin was reconstructed to have occurred within early Miocene. It was suggested that the Indopacific-Mediterranean seaway was closed during late Burdigalian about 17 Million years ago. From that time onward larger animals could migrate from Africa to Eurasia and vice versa. Mammal exchange across the Levant Region was noted to have occurred first by African invaders to Eurasia among them elephants (probosideans), Tragulidae (mouse deers), anthracotheres (hippos), and the African rhinoceroses. East African representatives of hominoids did not enter Eurasia until middle Miocene and they met the Eurasian mammals which crossed over to Africa including the felines (cats), canids (dogs), hyaenids, viverids (civets), equids (horses), advanced rodents and lagomorphs (rabbits and hares). The latter were reported not to have been known from Africa prior to 12 Million years ago.

In the late part of the Alpine Orogeny the Paratethys Basin formed,It consisted of a chain of basins, partly filled with the debris of the rising mountains of the Alps, Carpatians and Caucasus. The Paratethys, at times, was flooded by the sea entering from the Atlantic –Mediterranean- Indian Ocean and had for example the Alpidic mountain chain at its southern margin with a gap at the Rhone Bay. In mid Miocene time, a large continental sea with exits to the Mediterranean Sea and to the Persian Gulf that extended from the Vienna Basin in the West to the Aral Basin in the East was present. In late Miocene time this sea turned into a brackish sea, later into a chain of more or less brackish lakes, in which a special fauna evolved with many new species. Of these only after the end of the Tertiary a few migrated into the area of Jordan. It was reconstructed that the Paratethys during Late Miocene, perhaps also Pliocene time was connected by a narrow seaway with the Persian Gulf and also with the northern extension of the Jordan Rift system.

But for the 15 Million years that passed since the sea of Tayba time (that had come here from the Pacific Ocean became salty and deposited salinal beds and the probable latter deposition of salt coming from the Mediterranian Sea and thus the Atlantic Ocean into the rift) no information exists so far to be extracted from deposits that were laid down in Jordan.

The history of the region during the Messinian salinity crisis of the Mediterranean Basin around 5-6 million years ago is also little known, but salt was probably deposited during that time. Pollen from the Jordan Rift area indicates that the region was quite dry, but that in lowlands also marsh forests existed with savanna nearby. The Mediterranean basin was at times almost empty of water and in its eastern part lay several kilometers deep sea with a salt lake in its base. In Messinian time, the base level for subaerial erosion fell by about 3.5 km. It was assumed that due to the removal of water load from the Mediterranean crust and the subsequent reloading within a period of about 1 million years repeated large shocks could have affected the earth’s crust adjacent to the Dead Sea transform fault. Also during the Messinian low stand of the Mediterranean Sea the Nile excavated a deep canyon and its fauna could meet with the endemic fresh water fauna of the Paratethys that invaded the Mediterranean through the Aegean.

Post Messinian Jordan

In the final time of the Miocene the connection of the Mediterranean Sea with the Atlantic Ocean was closed. Subsequently much of the water of the Mediterranean Sea evaporated during the Messinian stage that lasted for about 700000 years and large parts of the former sea bottom became dry land. This salinity crisis and major regression caused deepening of erosion channels, for example a deep canyon was eroded by the river Nile. Near Kairo this canyon was about 2.500 m deep and when the sea returned. during the Zanclean flooding event, about 5.3 Million years ago the canyon was filled by sea water which reached up-river as far as Aswan forming a Nile Fjord. Also the area of Jordan was stongly affected by this salinity crisis of the Mediterranean Sea. The area occupied by the present-day Jordan Valley became connected to the Mediterranean Sea probably through the Bisan (Yizreel) valley that nowadays ends near Haifa. When the level of the Mediterranean Sea dropped dramatically a canyon was eroded that captured the drainage system within the Jordan - Dead Sea depression. Even though the two basins of the Lake Tiberias and the Dead Sea within the Jordan Rift continued to downfault, they were probably connected to the eastern Mediterranean basin with erosion channels. During this Messinian salinity crisis that began about 6 Million years ago, a huge Dead Sea-like lake at the base of the Levantine slope formed in the eastern Mediterranean Sea that had its base at times more than 3000 m below sea level. With this deep trough a canyon at the Bisan valley probably established a connection of the Jordan Valley Basin area to the Mediterranean Sea Basin.

When the Mediterranean area reopened its connection with the Atlantic Ocean through the Straits of Gibraltar the Zanclean flood filled the Basin of the Mediterranean Sea with sea water which also entered Bisan valley (Yizre'el Valley) and through it the Jordan Valley and here the Basin below modern Lake Tiberias (Sea of Galilee). The sea may well have extended to the area south of the Dead Sea to the area of Jebel er Risha. This water evaporated within the depression of the Jordan Rift and was obviously replenished for an extended time first flowing freely from the Mediterranean, later perhaps seeping through the sediments and the logoons which began to occupy the Bisan fjord. This Tabianian Sea left, up to 40 m thick oolitic limestones, some containing Foraminifera and Ostracoda south of the Dead Sea in Wadi Araba (Jebel er Risha) area. Marine sediments partly formed in lagoons in the Bisan valley (Bira Formation). In the subsurface near Lake Tiberias they consist of about 150 m of marls, clays and sands locally deposited in saline lagoons, often under brackish conditions. At other localities a conglomerate (Um Sabune) is found overlain by evaporites (Menahemya Gypsum). To the south rock salt, anhydrite, and clay comprise the Mount Sedom Formation and in it, similar pollen were determined as in the sediments of the Bira Formation in Bisan valley.

The downfaulted areas within the Jordan Rift such as the Dead Sea Basin and a basin near Lake Tiberias (Kinnarot Basin) were filled with sediments that can not be studied on the surface but are only found in the subsurface, with rare exceptions as in Sodom and Gomorra at Mount Sedom, where salt has been pressed up in a diapire. Diapicic occurrences of salt and gypsum are also found near the Karama reservoir in the Jordan Valley south of the mouth of Zerqa River. Here salt of the salt dome leaks into the water which therefore has turned to be quite salty and useless for irrigation. Folded gypsum layers next to Karama lake and close to the dam of the revervoire pierce the surface and also south of the dam where the salt dome reaches the surface.

Next to the southern end of Lake Tiberias and to the mouth of the Yarmouk River into Jordan River on the west side of the Jordan a drill hole penetrated almost 4250 m of the sediment of the Tiberias Basin, much of it consists of salt. The basal sediments encounterd by the bore hole consist of about 7 m of red beds of conglomeratic material with pebbles of Cretaceous, and Eocene limestones and some basalt. The reported presence of basalt pebbles is quite distinct from the gravel as occurs within the Tayba Formation which is without basalt. Above the conglomeratic base that may represent deposits of a river about 2000 m of mainly salinal deposits have been recognized. Into these at about 3-4 Million years ago magma intruded and formed thick beds of gabbro. That is volcanic basalt that had sufficient time for cooling and crystallization of its minerals which, therefore, are larger than those found in the magma that came to the surface and here cooled more rapidly. The gabbro may be related to the basalt which belongs to a large volcanic field that extends from northern Israel-Lebanon and Syria across the eastern extension of Jordan into NW Saudi Arabia covering a very large area. These plateau basalts have begun to erupt with the begin of the Miocene connected to deep crustal movements which were also responsible for the formation of the Jordan Rift. The Cover Basalt present near Umm Qais has been dated to have been emplaced at about 3-2 Million years ago. Basalt flows can also were responsible for closing the connection of the Mediterranean Sea to the Jordan Rift-Dead Sea.

The large amount of salt that was deposited in the rift is assumed to have come predominantly from the Mediterranean Sea partly perhaps during and predominantly after the Messinian salinity crisis. The brackish and hypersaline conditions, according to the pollen that were extracted from the sediments, have been dated to have been present at Miocene-Pliocene time. Near Lake Tiberias the sequence at the drill site above the salt is about 150 m thick and is overlain by 500 m of basalt.

Near the town of Ghor Safi and in the Lisan Peninsula of the Dead Sea data indicate that deposits coming from the eastern side of the rift consist of sand and gravel and that they intercalate with salt coming from sea water originally of the Mediterranean Sea. Salt and gravel were deposited in a rapidly subsiding rift valley side by side within the Dead Sea basin forming deposits of about 3000 m in thickness. In the northern Jordan Valley just south of Lake Tiberias Messinian and post Messinian Pliocene sediments are overlain by freshwater sediments of the Gesher Formation. It consists of 20-50 m of limestone, clay and marl which were deposited in a lake that predates the Cover Basalt of late Pliocene age. Gesher lake was populated by feshwater molluscs such as *Melanopsis*, *Melanoides*, *Hydrobia*, *Viviparus,* and *Dreissena*. Similar fauna has been observed further north in the Beqa'a in Lebanon as well. Most interesting is the presence of the gastropod *Viviparus* and the clam *Dreissena.* Both had probably arrived here by migration from the Paratethys on a route that in general followed the modern Orontes.

Ornamented species of the gastropod *Viviparus* resembling those known from Pliocene lake deposits are found on the islands of the Greek Dodenkanes (Kos and Rhodes) and the nearby Turkish mainland, and they probably migrated into Lake Gesher. *Viviparus* is quite a large gastropod living in fresh water with its life cycle including a brood-chamber from which young hatch with the organization of the adult and a shell consisting of several whorls. The species from the Gesher Formation resembles species as they lived in the Paratethys Basin during the Pliocene with triangular shell shape and thick walls compared to the usual types present in Europe with rounded whorls and thin shell. *Viviparus* feeds by filtering algal cells from the water with its large gill and taking hold of the collected cells from a food stream transported by cilia to the side of the head by the mouth and the teeth of the small radula.

Dreissena resembles a mussel, but is not related to it, and in contrast to it lives in fresh water. Like the mussels (*Brachidontes*) from the Gulf of Aqaba *Dreissena* lived attached to hard substrates by its byssus threads, but in contrast to them the shell has no nacre but is composed of crossed lamellar structure. In historic times *Dreissena* has again left its origin near the mouth of the Volga River into the Caspian Sea and, aided by humans has conquered many fresh water lakes and streams in many parts of the world. It could have reached Lake Gesher attached to the feet of feathers of migrating birds. That lake may have also drained northward through Beqa’a and Tripoli. The height of the land present at that time cannot have differed much to the North and the South of Lake Gesher, while nowadays the northern connection is barred by thick volcanic deposits.

During deposition of fresh water deposits in the Northern Jordan Valley, in the Dead Sea Basin it has been suggested that the Amora Formation was laid down, consisting of up to 400 m of conglomerates, shales, dolomite, and rock salt. The shales are partly freshwater deposits with remains of a water plant suggested to represent *Valisneria* which is a freshwater plant of the Hydrocharitaceae, commonly called eelgrass. It lives submersed and spreads by runners and sometimes forms tall underwater meadows. Elongate leaves with round tip and parallel veins arise in clusters from their roots. This plant can be confused with *Zostera* species, marine sea-grasses, that are usually also given the common name "eelgrass" and live in the sea, for example the shallow lagoon at Aqaba. Also *Potamogeton* of the Potamogetonaceae (pondweeds) that appears in salty creeks in the modern Jordan valley which issue from the salt dome top at the eastern side of Karama reservoir and can have a rather similar habit of its leaves and shoots forming underwater meadows.

The lake in which Al Qarn Formation was deposited contained no more *Dreissena* and *Viviparus* which had become extinct in the area. Al Qarn Lake existed at late Pliocene or early Pleistocene only in the northern part of the Rift in Jordan. It formed above river gravel and was filled by river deposits carried here from the rising highlands to the east. The rivers periodically transported pisolites which had grown in cyonaobacterial crusts within the soil and were washed from it when this soil was eroded (Fig. 113). Floods transported them into the river and from there into the basin. Before and after the events of more or less local soil erosion the river gravel was predominantly composed of eroded Paleogene and Cretaceous sediments. Al Qarn Formation is exposed at the eastern banks of the King Abdalla Canal (Ghor Canal) just to the west of the village Abu Habil and just to the south of Jebel al Qarn where it overlies the Oligocene-Miocene deposits of Tayba Formation with angular unconformity. The lower part of the lake deposits holds some pisolitic beds, in which the pisolites were sorted according to their size. Beds composed of small pisolites resemble oolites and can easily be mixed up with them. But while these pisolites were on land in soil, oolites form in the shallow sea, and when they are mixed up with each other, interpretation of the original environment can be very wrong.

Lake deposits of Al Qarn Formation are composed of fine quartz sand mixed with marly calcareous sand of about 25 m in thickness and with its strata dipping with about 50° towards the center of the Jordan Valley. A gravel layer above the lake deposits in its upper part is composed of large pisolites with concentric composition, as they formed at the same time in the hill sides and mountains nearby. Original soil containing oncolites (=pisolites) of different sizes is exposed for example next to the road from Waqqas to the highland and to the village Tayba. Here also a small about 5 m thick canal filled with reworked pisolites, is exposed right next to pisolite rich soil untouched by erosion. Calcretes (caliche) covers an extensive area over calcareous bedrock by upward percolation of groundwater through surface evaporation and the biological influence of cyanobacteria. When the lake existed, climatic conditions were more humid than today, so that the pisolites forming in the soil during strong rains could be washed from them, concentrated and deposited as river gravel.

Fig.113: Conglomerate composed of pisolites as present at the top of Al Qarn Formation.

The sandy sediments of Al Qarn Formation have some beds consolidated by calcareous cement with formerly aragonitic shells becoming dissolved. In the beds with well preserved fauna this sand is still unconsolidated and contains more clay. Its fossil content can be washed from it. The molluskan fauna is rich and holds besides small bivalves of the *Pisidium* type, several gastropods with several species of *Melanopsis* quite visible in the field and also *Theodoxus*, *Melanoides*, *Bithynia*, several small hydrobioids, *Ancylus*, *Gyraulus*, a lymnaeid species, and *Valvata.* A variety of stylommatophoran pulmonate species and *Pomatias* were washed into the lake that were, formerly living near it on land. The land snails have thin shells in which the original organic shell material has been decomposed so that they do not survive the washing process of the sediment. But their initial whorls are more solid and well preserved. Here shape and size of the embryonic whorls documents that they belong to land snails. Their early life usually begins in relatively large eggs with much yolk available to the embryo and the young hatch with a much larger shell than is found among the species of fresh water gastropods. Species determination of land snails can be of value in the reconstruction of the climate, since data regarding the living land snails of the Levant are well known. Fragments of vertebrate bones are present as well as teeth that could have come from a crocodile. Ostracods and crab claws of *Potamon* represent the crustacean inhabitants of the lake. The fresh water crab *Potamon* still lives along most creeks and rivers in Jordan, as amphibious animal with rapid movement on land, as well as, in water. During day times it usually hides in burrows which it excavates at the margin of creeks.

Most gastropods from Al Qarn Formation still have living relatives in Jordanian fresh water creeks and ponds, with the exception of *Bithynia* and *Ancylus*. *Bithynia* is a member of the Caenogastropoda with a calcareous operculum that has a characteristic concentric composition. It lives all over Europe represented by a few species. The species from Al Qarn with the shell about 5 mm high and 3 mm wide consist of 5 whorls. The absence of the umbilicus and pointed conical shape is a characteristic to the genus. The operculum is thick and concentrically lined on the outside with small spiral nucleus which provides protection from crab attack. Living species filter phytoplankton from the water with their gill and collect additional food with the snout.

Ancylus is a small fresh water limpet belonging to the Pulmonata (Basommatophora). Their eggs contain much liquid yolk and during early ontogeny the embryo grows so rapidly in size that the shell calcification is retarded until the limpet shape has been reached. A coiled shell is no longer present at all, as is characteristic to the living species of the group. *Ancylus* hatch with about 1 mm large cap-like shell. The specimens from Al Qarn are quite characteristic but the genus has not survived in Jordanian waters. *Ancylus* is usually attached to some object, a stone or another shell and it grazes on algal covers. The individuals of Al Qarn Lake lived on the submerged stems of reeds or on larger shell near the beach with currents produced by the waves.

Theodoxus occurs in almost all clean springs and creeks in Jordan. The species which lived in Al Qarn Lake are very similar in shell shape to those that live in the Yarmouk River, in Lake Tiberias, and in the Orontes. *Theodoxus* has a short shell with few whorls with a thin outer calcitic layer and a thick inner aragonitic layer. The color pattern lies within the outer calcitic layer and can be well preserved in fossil shells as in the case of the Al Qarn specimens. Ornament often consists of stripes in zigzag pattern which is very variable within the same species. The color varieties of the now living populations have often been placed in different species according to such patterns, and among fossil *Theodoxus* a profusion of names exist. Not only color but also shell shape may vary from simple and rounded and as wide as high to higher than wide and angle at their apical side and/or a groove on the side. Among the now living *Theodoxus* in Jordan those individuals living in the Yarmouk River and sometimes also in the King Abdullah Canal (KAC) right besides the outcrop of Al Qarn Formation may have a corner around their apical shell portion and striped shell pattern, as is also present in varieties of Al Qarn *Theodoxus*. Individuals from springs and creeks in Jordan are usually rounded and shiny black, sometime dark and dotted. Their operculum is calcareous and has a peg on its inner side with which it is held in place when the animal is withdrawn into its shell. This protection is quite effective and can prevent the crab *Potamon* to use *Theodoxus* as food. The specimens of the population of KAC have their embryonic shell, which composes the first whorl, clearly set off from the teleoconch by white coloration. The teleoconch consists of about 2.5 whorls, as is also the case in *Theodoxus* from clean springs and creek in Jordan.

In the case of *Melanopsis* the crab *Potamon* is often more successful and can crack the shell beginning at its aperture. Its operculum is organic and not as protective as the calcareous one of *Theodoxus*. *Melanopsis* still represents the most remarkable gastropod found in running fresh-water in Jordan. In a clean stream individuals may be very common and present on each pebble in the stream bed. The oldest representative of *Melanopsis* in Jordan is found in Al Qarn Formation. The snail feeds on all kinds of organic material found in a stream. When found together with *Theodoxus* in a creek on rocks the later dominates, since it is more efficient to scrape off algae with its radula. *Theodoxus* has the harder teeth which are even partly mineralized with iron oxide. The radula of *Melanopsis* is more efficient, in raking, in rotting plant material. The dark shell of *Melanopsis* is up to 4 cm high, has a cyrtoconoid outline with the body whorl more or less inflated and whorls of the spire hardly rounded and smooth or ornamented by axial and/or spiral ribs. Both types of ornaments are present in the Al Qarn fauna and also occur among the modern species living in Jordan, with some distinctions. Al Qarn *Melanopsis* is somewhat intermediate in shape in between the species as they lived during the Pliocene in lakes connected to the Paratethys (now they are exposed on Kos Island) and the species living in Jordan up to date. The egg-shaped aperture has a rounded outer lip, a short anterior channel and a smooth inner lip with a characteristic posterior callus pad. The young hatch, crawling with a shell of 0.2-0.4 mm, grows in eggs which are singly distributed on the bottom substrate.

The slender elongate *Melanoides* was well represented in Al Qarn Lake and it is only little different from the species that still lives in Jordan mostly on muddy ground in very shallow or in running water. In the sub recent lake of the Azraq oasis that has since disappeared, it grew to larger sizes no longer found in Jordan. *Melanoides* lives in the creek that flows through the village Hemma into the Yarmouk, occurs along the Jordan River to the Dead Sea on muddy grounds as well as in similar environment along the lower Mujib River and in Hasa River. It also lived in the Pliocene lake; Ubeidiya Formation. *Melanoides* has a rather special mode of life by its populations consisting of only females but males occurring only as exception. Thus a single individual can start a whole new population of many individuals. The female broods its young in a special pouch and releases juvenile provided with a shell of several whorls. This tiny juvenile can easily be transported on the feet or on feathers of water birds and can thus be spread easily over long distances. *Melanoides* nowadays lives in Jordan also when water is a little brackish as it was in Karama Dam Reservoir, but water salinity has increased here and *Melanoides* became extinct in the lake.

Valvata has a small trochiform shell consisting of three whorls and with a little more than 2 mm in diameter. This species is common in lake deposits and can be found, in some creeks in Jordan, still living in the area extending from a spring in Wadi Rum in south of Jerash in the north. It prefers clean fresh water. The similar but not related *Gyraulus,* has a preference to plant rich environments and was also common in Al Qarn Lake, but occurs nowadays only rarely in the fresh water of Jordan.

Ghor el Katar Formation which was typified as exposed 2 km SSE of Kureiyima a town to the north of Deir Alla and south of Abu Habil may include lake deposits resembling those of Qarn Formation. The latest Pliocene landscape of Palestine, Israel and Jordan has been reconstructed as a rather extensive flatland occupied by two drainage systems, the main one leading to the Mediterranean, and a subordinate one leading to the Red Sea. These drainage systems were interpreted to have been rather flat, meandering with relatively wide river channels, which traversed the entire country connecting the Jordanian Plateau with the Mediterranean. This reconstruction can not be supported when the gravel beds are considered which under- and overlie Al Qarn Formation and give evidence for relatively strong erosion near the margin of the northern Jordan Rift. The deep basins of Lake Tiberias region and of the Dead Sea region were obviously connected to slopes on which erosion was at work. Many areas of the Levante were not considerably elevated above average sea level. Ancient rivers transporting eroded material across the region appear for a long time to have had a general east-west direction. Such ancient river beds filled with conglomerates are exposed to the south and west of Irbid along the banks of the roads to Amman and to North Shuna. Their load may be connected to the Um Sabune Conglomerate of the Central Jordan Valley that consists of coarse conglomerates attaining up to 200 m in thickness and overlying the Lower Basalt covering an erosional relief. The time of formation of these river beds has not been well established up to date. The pebbles found in their beds may have joined the conglomerates that were deposited in the Jordan Rift at the time of Tayba Formation about 20 million years ago and again before the time of the existence of Lisan Lake about 50000 years ago, including the Abu Habil congomerates of unknown age on the eastern side of the Rift and those that underlie and overlie the Al Qarn Formation. The beds of Al Qarn Formation were deformed and eroded by the meandering Jordan River before the valley was flooded by Lisan Lake.

Aramshi Formation forms the flat carbonate rock plate that covers Tall al Mudawwar that lies about 2 km north of Waqqas next to the village Fathiyin (Aramshi). This carbonate deposit rests on the top of a small truncated basalt sill. The massive solid limestone at the base holds many gastropods of which *Theodoxus* is most clearly recognized but also *Melanopsis, Melanoides* and small planorbids occur. The basal gastropod rich layer is overlain by massive solid limestone with roots and *Stromatactis* like structures as well as pisolites. The top of Tall al Mudawwar was the site of an ancient village, while the modern village lies on its southern base. The whole deposit appears to have been surrounded and flooded by the Lisan Lake at times, forming an island in that Lake. Aramshi Formation may be younger than Qarn Formation since it is less deformed, but may also be older since deformation of strata in the Jordan Rift depends much on the distance to the main faults. The depositional environment is that of a clear shallow lake provided with water from springs and surrounded by gentle morphology with soil in which pisolites developed.

The age of Aramshi Formation may also resemble that of Ubeidiya Formation dated to be about 1.4 to 1 Million years old for sediments 3 km southwest of Lake Tiberias. It is described as about 30 m thick consisting of alternating limnic and fluviatile deposits. Bedded clay and silt, oolitic limestone (probably washed and size-sorted terrestrial oncoids) and soft chalk contain *Melanopsis* and plant and fish remains followed by conglomerates holding implements as well as vertebrate bones among others, those attributed to *Homo erectus*. Its depositional environment has been interpreted to represent a river discharging into a lake with swamps. Bones of a fossil species of dogs (*Canis*), of hippopotamus, gazella, deer (*Praemegaceros*), fossil horse (*Equus*) and also small shrews (*Crocidura*) were excavated from the beds of Ubeidiya Formation.

A travertine deposit at the southern end of Mashara town forms a hill with its layers dipping towards the south. It was deeper in the valley at a level below highest Lisan lake level and lies above the deposits of the Pre-Lisan-Jordan. This travertine had formed before the existence of Lisan Lake and presents evidence for a fresh water spring that existed in that place for some time. Travertine is developed at many springs of Jordan often within mats formed by cyanobacteria, but also on plants. Its source is the water which is saturated with bicarbonates passing on its way through the subsurface through carbonate rocks or with sources of bicarbonates surrounding areas of ancient volcanic activities. Cyanobacteria and plants need CO2 for their photosynthesis and thus utilize CO2 from the Hydro-Carbonate and reduce it to Carbonate. CaCO3 which is much less soluble in water than Ca (HCO3)2 and is deposited near or on the CO2 breathers, thus calcifying them. In addition, when thermal water saturated with respect to bicarbonate discharges to ground surface, it releases CO2 and carbonates precipitate. Travertine in Jordan forms near springs with normal temperature of the water and in that case the carbonate deposits have a more irregular growth of lime than those formed near springs with thermal water. This difference is based on the mats of cyanobacteria which grow faster in the case of the warm or hot water springs and thus spread over a larger surface which grows to a mat. That can very well be observed in the area of the thermal springs of Zarqa Ma'in where both types of springs, normal temperature and hot occur close to each other. The travertine hill near Mashara was formed by a spring with normal water temperature. Probably also the type of lime formed differs, with thermal water commonly aragonitic crystals grow, while with normal water temperature predominantly calcite precipitation.

The ancient Jordan River came from the North of the Rift valley and issued into the Paleo-Dead Sea. Its deposits are exposed along the steep slopes of the Zor that is the river plain formed by modern River Jordan (Fig. 114_. From near Deir Alla to the north up to North Shuna the slopes of the Zor expose the fluviatile sands, gravels and marls which are usually overlain by the laminated sediments formed during the existence of the salty Lake Lisan (fig. 115). Near the entrance of the Yarmouk River into the Jordan River these fluviatile deposits, below the Lisan Formation, are called Naharayim Formation. Further down-river and in stratigraphical position also below the Lisan marls, for example near Al Qarn Hills west of Abu Habil and west of Mashara, fluviatile sands locally contain gastropod shells belonging to *Melanopsis* and *Theodoxus* and also of two species of the bivalve *Unio*.

Fig. 114: Zor of the Jordan Valley west of Mashara, with sands of the ancient Jordan covered by laminated beds of Lake Lisan marls

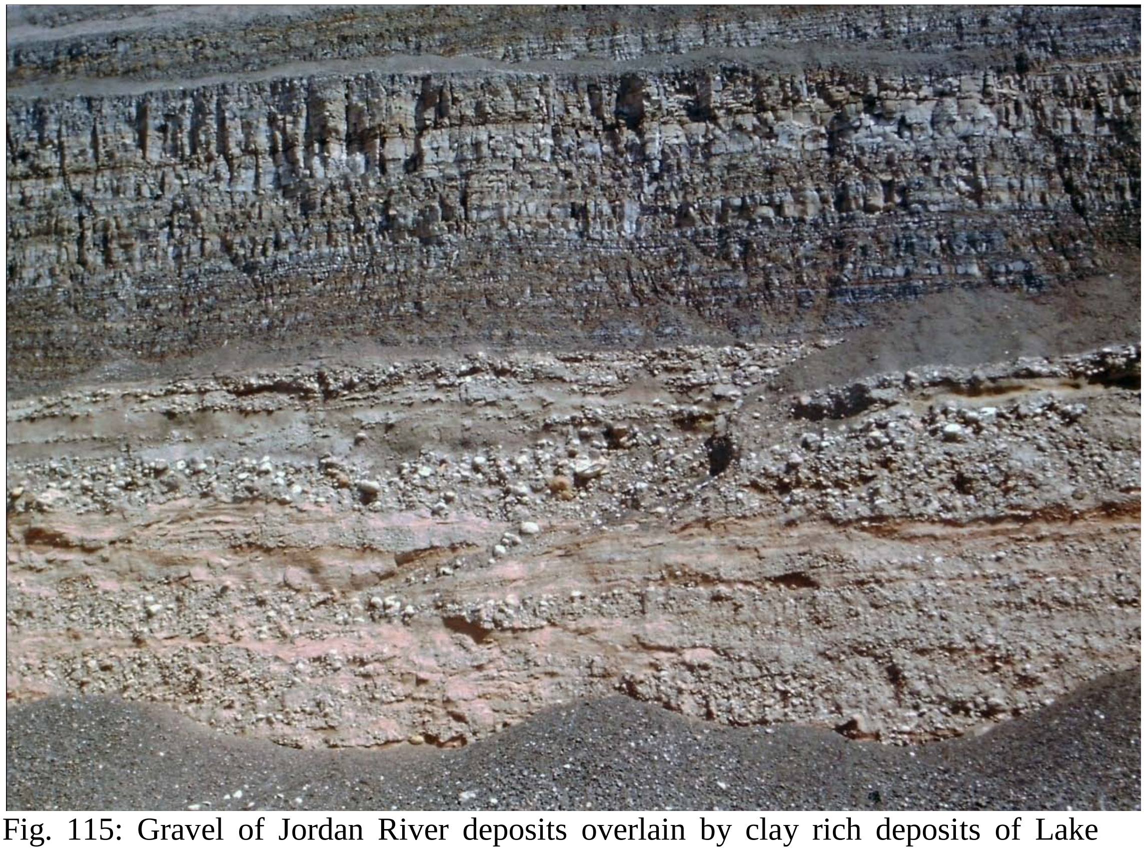

Fig. 115: Gravel of Jordan River deposits overlain by clay rich deposits of Lake Lisan. The sandy layers hold *Melanopsis* and *Unio*.

The bivalve *Unio* has an aragonitic shell and long oval shape. Its hinge is reduced in size and consists of a few low teeth. *Unio* belongs to the fresh water group of the Palaeoheterodonta among the bivalves which exists since Triassic time and has evolved a distinct mode of reproduction by parasitic larvae (Glochidia). Due to this adaptation the bivalve can move to all areas in a river system which can be reached by some fish living in it. Females of species of Unionidae have their gills transformed into large pockets in which several hundred-thousand eggs are brooded until they have grown their shells, and they are ready to hatch. These Glochidia have two valves with a hook on their margin and a strong muscle connecting them with each other. When a fish comes in contact with the exhalent siphon of the bivalve the larvae are expelled. They have their valves gaping and a special gland of the foot spins a sticky mucus thread. Thus several individuals are usually connected with each other by their mucus threads and form groups of individuals. When they come into contact with the skin, or even better the gill of the fish, a sensory hair reports this to the large retractor muscle which contracts. Thus the valves close and their marginal hooks penetrate the skin of the fish. Since several bivalves are connected by their byssus threads the process of attachment to the host is improved. The tissue of the fish reacts to the irritation of the skin penetration by growing around the bivalve larva and inclosing it in a cyst. The glochidia thus enclosed by tissue of the fish feed from lymphatic- liquid of the fish for an extended time that may last several months. As soon as the larva has grown as parasite of the fish, and during this growth changed shape of shell and body organization into that of a small juvenile, it breaks away from the cyst and falls to the ground of the water at a locality to which the fish has moved by then. From there on and until adult stage is reached, often several years later, *Unio* behaves like many bivalves, lives half buried in the ground and filters phytoplankton from the water of the river. In Jordan nowadays two species of *Unio* live in King Abdalla Canal near to its intake from the Yarmouk River and they also live in Lake Tiberias, together with a *Corbicula* that might have been living here since the Pliocene but may also have become introduced here by man in recent times, originally coming from south-eastern Asia. The *Unio* of the Paleo-Jordan deposits does not differ from the now living species.

From Nahayarim Formation, pollen from beds overlying the Yarmouk Basalt and overlain by the Lisan Formation, were analyzed. They document that the flora resembles that living here today except for those introduced to the area by men. The sands of the Jordan River are cut by channels of different sizes filled with gravel, and some of these channels, during the deposition of the sediment filling them, contained quiet water in which mud was deposited, some of which is calcareous and some may hold minute pisolites resembling oolites. From the side fans of debris which entered the Jordan Valley to reach almost its center were quite different from the condition of nowadays where fans of debris only reach to the margins of the Jordan Rift valley but not the Zor. The Jordan River thus, in Pre-Lisan times, took its way in a less steep valley with further advancing debris fans of its side creeks. Nowadays the Jordan River erodes its bed predominantly into pre- Lisan deposits.

Transition from these fluviatile sands to Lisan Lake documents quite well, that the waters of the lake came slowly, and the area turned into a swamp at first with much organic material entering the sand. As soon as the lake had flooded the soil, finely layered (varved) sediment was deposited that in its composition reflected differences of sediment formed during winter and summer. Life in the lake was quite restricted and only microbial organisms may have settled the bottom substrate which could not disturb (bioturbated) the fine bottom mud. The water of Lisan Lake provided the living environment for some species of diatoms, but it was throughout its existence so salty that gastropods and bivalves never entered it, even though springs and creeks issuing into the lake usually contained them.

The Lisan Formation is thus a product of the Lisan Lake during the time when glaciers of the Würmian/ Weichselian ice age covered much of Europe between 80-15 thousand years ago (Fig. 116). The finely laminated Lisan marl received its name from the Lisan Peninsula extending like a tongue into the Dead Sea. Lisan Lake was up 240 km long extending from the southern margin of Lake Tiberias to the south of the Dead Sea and extended across the whole rift valley engraving its former beaches along its slopes. Terraces at –150 m were measured in Wadi Araba to the south of the Dead Sea and sea level at - 150 to - 165 m is interpreted to represent the highest stand at around 25000 years ago (Fig 117). Near Deir Alla a maximum level of -164 of the Lake Lisan water was measured, while - 160 m were determined at Wadi Al Hammeh just to the north of Pella (Fig. 118). Terraces are very well imprinted in the mountain slopes along the eastern Dead Sea and can easily be traced from aerial photos of the region. In addition to the Jordan River in the north, other source of fresh water contributed substantially to the water budget of the lake and many of the deep canyons, as for example that of the river Zerqa Ma'in had been filled with gravel up to the highest level of Lisan Lake.

Fig. 116: Zerka Ma'in with basalt eroded to form the pre-Lisan valley into which the modern valley has been cut

Fig. 117: Terraces of former Lake Lisan at the mountain flank at Wadi Tayba near the southern end of Dead Sea (below Wadi Uhaymir)

The offshore deposits consist mainly of calcareous sediments and silts containing abundant diatoms. The light laminae of the lower laminated series are usually monomineralic, composed mainly of aragonite needles, frequently associated with diatom frustules forming in the dry summer season. The dark laminae are composed mainly of calcite associated with clay forming during the wet winter season when water from the land entered the lake, loaded with suspended mud. In the white lamina the diatom genus *Nitzschia* is present that occurs in brackish water, while the dark zones have fresh water species of genera *Gomphonema* and *Rhopalodia*.

Diatoms occur in the fossil record only since the Jurassic and they live nowadays wherever it is wet, with most species living in the sea. The silicate shell consists of Si (OH) 4 and is constructed of two parts which are fitted together like the two parts of a shoe-box and reach a size of up to 0.1 mm. The shell lies on top of the cytoplasma and both parts are held together by plasma-fibers. Free floating species use drops of oil in the cell as floating device compensating their weight in the water and keeping the cell afloat. The planktonic ones are part of the phytoplankton and other live benthic and can move on the ground by special organelles which leave the shell interior along a slit on the base of the skeleton. When reproducing, both parts of the skeleton are pulled apart and the missing smaller one is newly deposited. Vegetative reproduction changes with sexual reproduction with the formation of free swimming sperms and eggs. Diatom species can be used as indicator species of salinity. Each level of salinity of the water is preferred by special species and that preference was used to reconstruct the salinity of former Lisan Lake. Since the fossil species still have living representatives with their help lake history can be traced from a brackish lake at high water stage to the saline modern Dead Sea and to the freshwater-Lake Tiberias. But the opal of the skeleton easily dissolves during diagenesis and thus diatom shells are often no longer present in many of the Lisan deposits.

Fig. 118: Ancient shore line of Lake Lisan, north of Waqqas.

The ancient shores of Lisan Lake can be studied along the slopes to the Dead Sea, North of Zarqa Ma'in and with quite different characters north of Mashara in several places and especially well in Wadi al Hammeh just to the north of Mashara. A perennial warm mineral spring Hammet Abu Dabli lies about 3 km upstream from the edge of the rift valley. At the mouth of Wadi al Hammeh an intercalation of washed travertine debris and mud layers with clasts and sherds of dried mud surfaces give evidence of the former shore of Lisan Lake at about –150 m. Obviously, the lake level fluctuated and the muddy shore dried out periodically. The spring reeds and other vegetation formed the nucleus for calcification and the formation of travertine. Smaller particles of carbonates were washed and sorted according to size on the ancient beach in layers forming calcareous sand with the particles having concentric construction. The deposits of these springs of small calcareous grains thus resembles an oolite but have quite a different origin than the ooids which form shoals in the tropical sea.

During the long history of Lisan Lake water level fluctuated to large extents, exposing and later covering the slopes next to the springs repeatedly. It was reconstructed that water level during the existence of the lake fluctuated for about 100 m up and down, highest around 25-26 thousand years ago. The result is a very complex mix of generations of former valley slopes and gravel channels that have been successively consolidated by the calcareous deposits of the springs. Whenever lake level dropped, the creek in Wadi al Hammeh incised into the deposits deposited before and caused the flanks of the filling to become instable and, when consolidated by calcareous cement to slide down in smaller and larger boulder of angular shape. Thus boulders may represent deposits of a former pebble filled channel which therefore can have quite inclined bedding. Other such boulders consist of fine calcareous sand deposited in a creek with smaller flows into which small pebble channels were eroded, with inclined bedding of the different boulder differing from each other. The last pebble channels which formed next to the travertine mass are still found without slumping, but are cut by the last formed slope when Lake Lisan finally withdrew from the area at around 15000 years ago and relatively rapidly concentrated into the Dead Sea. In the upper valley level, behind the travertine bar, the muddy creek deposits of the Lake high stand, are preserved and contain *Melanopsis*.

Fossilized *Phragmites* and remnants of other grasses and bushes such as *Tamarix* are common in the travertine present on the edges of the valley. *Melanopsis* shells were analyzed and their age was determined by radio-carbon analysis to be about 15000 to 30000 years. The soil sequence present next to the valley consists of an upper soil of lighter color, somewhat reddish containing abundantly oncoids of different shapes and sizes. Below it, with a sharp boundary, the soil is more clay-rich and has remains of roots or a clearly developed root horizon. This is an indication of a wetter period.

The ancestral valley of Wadi al Hammeh is filled with 60 m of sediments including dark clay, silt and layers of pebbles and conglomerates. The clay formed from weathered rocks of the chalky-marl rocks of Muwaqqar Formation exposed next to the valley. When eroded and washed into Lake Lisan it is deposited in clay beds intercalated in the laminated authigenic Lisan deposits commonly consisting of thin, up to 1 mm thick aragonite layers alternating with layers which also contain clay and fine sand. The aragonite formed in the surface water of the lake which was received during the rainy winters and evaporated during hot, dry summers. The material of the detrital layers came from dust blown in from the sides of the lake and from turbid flood water entering the lake. Thus these layers reflect the change of fresh water of the rainy winter and evaporation and dusty winds of the summer. When water evaporated even more gypsum was precipitated in the summers, as is the case in the saltier water approaching the salinity of the Dead Sea.

Directly next to the Dead Sea the uppermost terrace formed by Lisan Lake is often a quite visible plane within the otherwise steep slope of the highland to the Rift. Here ancient and sometimes still active springs are connected to travertine. Often large boulders of travertine formed at different times and different lake levels are present on the slopes. The terrace not far to the south from the road leading from Madaba to the Dead Sea (Panorama Road) about half down the slope has a very conclusive beach preserved. Above it, the ancient spring is seen and from its deposits large travertine boulders have fallen onto the plane of the terrace. The shore of the Lisan Lake here had not only carved the terrace but it also built solid massive beach rocks. These are partly composed of laminated layers and of angular fractured particles of older, reworked beach rocks. A most telling feature here lies below this ancient beach with numerous conserved stromatolite nodules and knolls which lived in the water. This water may have been quite salty since similar cyanobacterial knolls of the shape just as these stromatolites still form in the Dead Sea at places where fresh water enters it just below sea level and near the shore. The water of Lake Lisan was probably also layered with a lower brine and an upper, less saline water body. The thickness of the upper water may have been only a few meters thick. The lake level also caused the corresponding ground water level to be raised and springs discharged their groundwater higher up than today.

Lake Lisan reached in the North the mouth of Yarmouk River near Menahemya on the western side of the valley and its salty waters did not enter the basin filled with ancient Lake Tiberias, which during the period of existence of Lake Lisan held fresh water with the characteristic fauna, of which especially *Melanopsis* living near and on the beach with its aragonitic shells provide the data by which the age of the lake in its different portions was well established. It was documented that the Dead Sea brines did not cross the Yarmouk fan deposits, now at 174 m below sea level, even at the highest stand of the lake 27000 to 24000 years ago. Fresh water Lake Tiberias existed during the highest stands of salty Lake Lisan next to each other and with only very little difference in water level but with continued flow of fresh from the north to the south and from one lake to the other. Here, as in the rivers, creeks and springs entering Lake Lisan the fauna of fresh water had it limits and could not enter the lake in which only a specialized life consisting for example of cyanobacteria on the ground and some diatoms in the plankton was present.

The post Lisan period can well have been the result of the reduction of the catchment area from around 157 000 square kilometers to about one fourth of that area. The rapid lowering of the water level and shrinking in the size of Lake Lisan near the end of pluvial times can be connected to the last phase of volcanic eruptions. Lava flows in the north – west, coming from Jebel Druz area, in addition to winter rains which washed a large wedge of debris from these, blocked the upper catchment of rivers Yarmouk and Zerqa. A new watershed formed between Zerqa and Azraq that lies approximately 20 m higher than the surface of Azraq Lake. The Wadi Dhuleil area which was connected to the Zerqa River was thus closed to the east. It represents a bed of fluviatile gravel and of playa basins of the former river with only weak inclination towards the west.

The lake in Azraq depression periodically had a size of approximately 600 square kilometers. It was surrounded by a zone of reeds and had trees along its shore. Into it small deltas were deposited from water coming along shallow depressions from the East, North and South. During the Pleistocene an about 150 m thick sequence of sediments collected in the basin, formed within more or less large lakes, and succeeding periodically dry mud flats. At one or several times the lakes had such a high salinity that *Cardium* of the bivalves and *Ammonia* of the foraminifera lived in it (Azraq Formation). In other periods it was filled in total or party by fresh water, also in sub-recent times, when fresh water gastropods such as *Melanopsis* and *Melanoides* lived here. Much of its sediment consists of the dust blown in from the desert in the East and South.

Water also remained in other parts of the Sirhan depression to which the Azraq Basin forms the northern most part. Within the Sirhan Graben periodically large shallow lakes formed in which water mostly evaporated and no continuous connection by one or several rivers existed. The sinking bottom of the Sirhan basin collected the fine sediment that was washed periodically from the large planes and hilly landscapes to the west and a divide separates gully systems and their wider dry streams going to the Sirhan depression in the east from those of the catchment of the Al Jafr Basin that occupies much of the desert of central Jordan and lies about 230 km southeast of Amman. Here also a former freshwater lake changed from conditions for life in fresh water to such in saltier water due to extended evaporation of its water. During the last pluvial period at the last ice age in northern Europe the Al Jafr Basin contained a lake that occupied an area of more than 1000 square-kilometers.

When the gully system imprinted onto the flint strewn desert is consulted distinct water sheds can be made out separating the Azraq Basin from the Al Jafr Basin. Locally it is evident that the creeks leading into the Al Jafr Basin eroded into the system of those leading into the Azraq - Sirhan basins. Thus Al Jafr Basin, at times subsided more rapidly than the Sirhan Graben to the east of it. Clearly younger than Al Jafr Basin are the erosions in the headwaters of Wadi Mujib and Wadi al Hasa. The river Mujib and Wala reach the border of the catchment of the Azraq Basin, while river Hasa contacts the northern margin of Al Jafr catchment SE of the town of Al Hasa. The upper catchment margin of river Mujib is clearly of a more ancient origin than that of modern Mujib, which is eroded into the surface of the earlier produced system of gullies west of Qatrana. The western margin of the Al Jafr Basin reaches the mountain range that accompanies the Jordan- Araba Rift. In the south, Al Jafr catchment borders with the western margin of the Yutum catchment along the crest of the mountain chain of Ras en Naqb. The whole area is called the Hasma and holds the catchments of two ancient lakes, Lake Disi in the west and Lake Halat Ammar in the east.

The desert regions of central Jordan collected during the last 20000 years and still collect water that enters the Azraq-Sirhan Basin and the Al Jafr Basin, while before that time some of that water flew to the Jordan Rift along the ancient connection to the Zerqa catchment by the way of Wadi Dhuleil.

In the south of Jordan two further catchments are present, one formed by the basin of Halat Ammar-Mudawara and the other by the Disi region of the Yutum catchment. Both have a border with the Al Jafr Basin and here the gullies erode into the system formed by the Al Jafr catchment. The boundary between Halat Ammar Basin and Lake Disi - Yutum catchment is less well expressed and can be considered a low continuation of the Ras en Naqb escarpment. The margins of the region from which the water was collected to flow into one or the other basin, thus, form the limit of the individual catchment areas of these basins and can be traced in the aerial photos presented by Google Earth (Fig. 119).

Fig: 119: Canyons cut into Paleozoic sandstones in the Disi-Rum area (the Hasma) have their basal portion subsequently covered by deposits up to a sea level of approximately 800 m which in part are those of Lake Disi that occupied the valley to a level of 844 m above sea level. The lake was present in all those areas now presenting light colored Qa bottom and somewhat beyond it. In the west crystalline rock is exposed and in the east predominantly Ordovician sandstones occur with their easternmost part already belonging to the catchment of Lake Halat Ammar.

Rain during the pluvial periods connected to one or several of the ice ages provided water for the existence of a large shallow lake, the Halat Ammar Lake (Mudawara Lake), on the flat highland in the Mudawara region (Madowwarah), which lies in the SE of Jordan but still well to the west of the Sirhan depression. The eastern and western shore of Lake Halat Ammar is bordered by Paleozoic sandstones which are partly covered by sands. Halat Ammar is the police station and former station of the Hedjaz Railway on the Saudi Arabian side of the border and Halat Ammar Formation is locally exposed SE of the village Mudawara in Jordan in trenches cut by construction works. The lake existed in a position of about 700 m above sea level, thus 100 m lower than the lake bottom of Lake Disi in the west. It has been suggested that Lake Halat Ammar existed during the equivalent of the Eemian warm period that existed in Europe before the last ice age, but it could also have existed during the last Weichsel ice age, which should also have caused a moister climate than now. When Lake Lisan grew in size during the time of the last ice age there was more rain in Jordan than before and after. Halat Ammar Lake filled with brackish water that, for quite some time, provided the living place for a fauna of bivalves and gastropods. Beds with many mollusks are up to 2 m thick and are connected to deposits of gypsum, clay and stone-salt. The mollusks may be included within cross bedded banks of gravel and the sand that could have formed at or near the former beach of the lake. The whole lake deposit is described as of about 12 m in thickness and the lowermost sandy beds have traces of a former system of roots. Shells of the bivalves *Cardium* (*Cerastoderma*) and *Brachidontes* and a small gastropod that resembles *Hydrobia* compose much of the sediment. A similar *Hydrobia* to that from Halat Ammar Lake and also determined as *Semisalsa* lives in brackish water of small creeks near the Dead Sea. Also abundant are shells of ostracods, and foraminifera of the *Ammonia* type and *Elphidium*. *Ammonia* has agglutinated shell, composed of sediment particles which were collected by the foraminifer by it protoplasma feet and glued together to form the walls. The same species can be encountered living in creeks formed by springs near the northern end of the Dead Sea. Here brackish water that issues from the ground due to the dry and hot surrounding turns into consecutively saltier water, and where the salinity approaches that of the sea, the foraminifer finds a good condition for life, as it did in the fossil lake. It probably reached that lake as did the bivalves attached to the feet of feathers of migrating birds. The most common ostracod of Lake Halat Ammar, *Cyprideis torosa* is also very common in a small pond formed by a creek from a brackish spring near Karama dam reservoir in the Jordan Valley. Here it forms mass populations, but this species can also be found living in Lake Tiberias and also in the brackish Baltic Sea. Other ostracods can belong to *Candona* species which also occur commonly in water with variable salinity. Interesting here, is that, besides single valves, many individuals of the bivalves and the ostracods are preserved with both valves still connected to each other. These animals were obviously killed before reaching full age and without valves detached from each other after death, which presents evidence for changing water level of the lake and the sudden death of the fauna in shallow regions due to desiccation.

The bivalve *Cardium* (*Cerastoderma*, cockle) usually lives in the sea, but varieties can also tolerate brackish water. Carried by migrating birds small individuals can be introduced into lakes, and this actually marine species can live quite far away from the sea, as was the case in Halat Ammar Lake as soon as it had reached a fitting level of salinity. The Faiyum Lake in Egypt lies at the end of a canal of the Nile and has cockles living in its brackish water. *Cardium* filters the water for phytoplankton and is also one of the most common bivalves inhabiting the intertidal flats of the North Sea. Here it lives shallowly buried just below the surface of the sand. It also occurs in similar environment in the Mediterranean Sea. From here their fossil counterparts had probably come to SE Jordan, carried by birds. The thick aragonitic shell has the beaks in front, is of oval outline and ornamented by radiating ribs. The hinge has unequal teeth and both valves are held together by the organic ligament, which is elastic and pushes the valves open to a narrow gape in the case the bivalve is feeding. When *Cardium* closes its shell it has to contract two about equal muscles. When the bivalve dies the shell opens due to the ligament that is still functional when muscle fibers are dead and even when the soft body is decayed. But after a relatively short period also the ligament decayed and both valves separated from each other, when moved by water current. The reproduction is by eggs and sperms shed into the water. Inside the fertilized egg the embryo develops and hatches provided with a shell. It swims as larva feeding on plankton for a few days until it settles to the ground.

Cardium occurs relatively common in lakes with salinity approaching that of the sea. *Brachidontes* in contrast is also common in the deposits of Halat Ammar Lake which is more unusual. The same or a very similar species lives in the Gulf of Aqaba and the Red Sea within the coastal lagoons and near the shore, but in contrast to *Cardium* it is attached by byssus threads to stones, or algae or sea grass. The shell of this *Brachidontes* is ovoid in shape with the hinge of many small teeth. The shell is composed of a thin calcitic outer layer and nacreous inner layer. *Brachidontes* has an ovoid interdissoconcha (special juvenile shell of approximately 0.5 mm in width) besides a normal prodissoconcha (larval shell). The straight hinge veliger (embryonic shell) measures a little more than 0.1 mm and the larval shell is about 0.3 mm in diameter. The ornament and shape of all four shells differ from each other and development stages can be recognized from well preserved fossil shells as well. The food of *Brachidontes* is the same as that of *Cardium* and it is also filtered from the surrounding water. On the blades of sea grass in the lake also the small hydrobiid gastropod collected its food consisting of unicellular algae. The vegetation in the littoral Gulf of Aqaba has no members of the group but species with similar shell shape occurred in the water systems of the Paratethys.

The catchment of Halat Ammar lake had its margin in the east bordering the catchment of the Sirhan depression further east in Saudi Arabia. The gullies leading into the Halat Ammar basin in the north intersect the gullies which belong to Sirhan catchment, thus are younger. At the headwater of Wadi Batn al Ghul which belongs to Halat Ammar catchment the watershed formed between it and Al Jafr Basin presents evidence for the erosion leading into Halat Ammar Basin. Thus Halat Ammar basin aggressively intruded marginally into the catchment of Al Jafr while this separation from the catchment of Disi- Wadi Yutum is weak.

Much relatively modern sediment formed in the lakes and the rugged sandstone mountains in the SE desert of Rum area. Former steep slopes and deep valleys became here locally covered during the Holocene by deposits transported by wind and water. The range represented by the Ras En Naqb and the mountains at its crest forms a water-shed with water north of it flowing to Jafr Basin to the north-east and south of it flowing towards the Qa ad Disi in the Rum – Ad Disi area. The southern run off eroded deep canyons cut into the Paleozoic sandstones. The large valley and canyons in Um Sahm and the sandstones below connects to Disi Aquifer which holds water that is approximately30000 years old. It appears to go in twists and turns along Qa al Ghuzlan (area of the park) into Disi. The former river shed its load into the Jordan Rift valley at unknown locality at the southern Wadi Araba or the Gulf of Aqaba. One likely former run-off towards Wadi Araba lies to the west of Quweira ending in what is now the Taba swamp dry lake with marginal springs in Wadi Araba. This system was closed due to uprising rift margin and canyon bottoms were drowned with sediment now forming the wide Disi and Wadi al Hiswa. The thus formed basin, during the last pluvial period, was filled with water up to the height of 844 m above sea level by a lake- the Disi Lake.

Disi Lake had its shore on the flanks of the Paleozoic sandstones of Um Ishrin Formation as has been checked in the field on three different mountain ranges, one right at Jebel Disi, the other 4 km to the west and a third one 6 km to the NW (above Rum Camp). Shore deposits are here preserved below the overhanging rocks of concave flanks which may have partly been excavated by the waves of the lake (Fig. 120). These deposits consist of coarser and finer sand alternating with silt layers. In them roots, pieces of wood and rocks fallen from the roof of the cliff are included. They were deposited on the beach of Disi Lake which was quite deep when the modern level of the Disi is taken as former lake bottom. It lies about 50 m deeper than the former shore in the mountains. The lake extended eastwards into Disi area and in the west to the base of the mountain range that accompanies the Wadi Araba near Quweira for about 35 km. Modern Wadi Yutum (Wadi Ithm al Jad) in its present orientation may well have formed within the last few ten thousand years and may have reached the Gulf of Aqaba via Wadi ar Ruwayna which connected to the fans of debris now found above the eastern shore of the Gulf of Aqaba between the Marine Science Station and the border to Saudi Arabia. The lower steeper part of Wadi Yutum that connects to Wadi Araba north of Aqaba and ends with a large fan of debris onto which much of the modern city of Aqaba has been constructed may be a product of erosion and deposition of the last thousands of years, since old Wadi Yutum has been parasitized. Even though Wadi Yutum lies dry for most of the year, occasional flash floods may transport much debris.

The Disi Lake filled former wadis with steep margins of the Paleozoic sandstone and received the water from the mountain range of Ras En Naqb, the Shara mountains, which rise to 1700 m. This range extends across southern Jordan into the NW of Saudi Arabia. Before Disi Lake could form the valley system of ist catchment was closed by uprising of its western margin and its lower portion filled with fine deposits. Structural rising of the western catchment area of Yutum (Yitm) has been documented near the ancient Nabataean site Humayma (Humaimah). Here Quaternary flood plain deposits onto which also an aqueduct had been constructed suffered severe erosion since the Nabataean period, with about 5 m per year advancement of gullies of the eastern valley leading to the Araba depression. This documents the continued rising of the western margin of the wide catchment which in its central portion held Disi Lake.

The rise of this western mountain range closed the ancient runoff courses and opened the way into Wadi Yutum which after existence of Disi Lake became the outflow of the catchment.

Fig. 120: Shore Deposits of Lake Disi in a recess into the Cambrian Sandstone at 844 m above sea level near the town Disi (seen below at about 795 above sea level).

A meteorite hit Jordan in the Eastern Desert in the Sirhan area some unknown thousand years ago and that impact left a conspicuous scar in the flint strewn desert. Jebel Waqf as Suwwan formed by this impact has a diameter of about 6 km and a prominent outer rim composed of chalks of Eocene age (Fig. 121). The flint layers and carbonate concretions in the chalks changed their composition dramatically when they were rapidly heated up during the impact.The concretions were baked from the outside and formed cracks,. The chert was heated to melt as indicated by its surface (Fig. 122). The impact did not only bake and melt rocks, but it also brought sections of the rock column to the surface which actually lay much deeper below the about 300 m thick rock sequence. From below it, about 50 m thick Amman Formation including the Ruseifa Formation, the around 300 m thick members of the Ajlun Group and even parts of the Kurnub Sandstone were detached from the subsurface, blown up to fall back and now form the central hill in the crater. This central uplift of up to 1000 m in diameter consists of large segments of the layers below. The formerly deepest ones, now predominantly in its center, consist of Kurnub Sandstone, next to it parts of the Cenomanian Turonian sequence with fossiliferous limestones are found, and the outermost consist of the characteristic limestone-flint intercalations of Amman Formation. The crater thus had reached at least 300 m deep into the ground with the blocks detached during its explosive formation now assembles around the central depression of the hills.

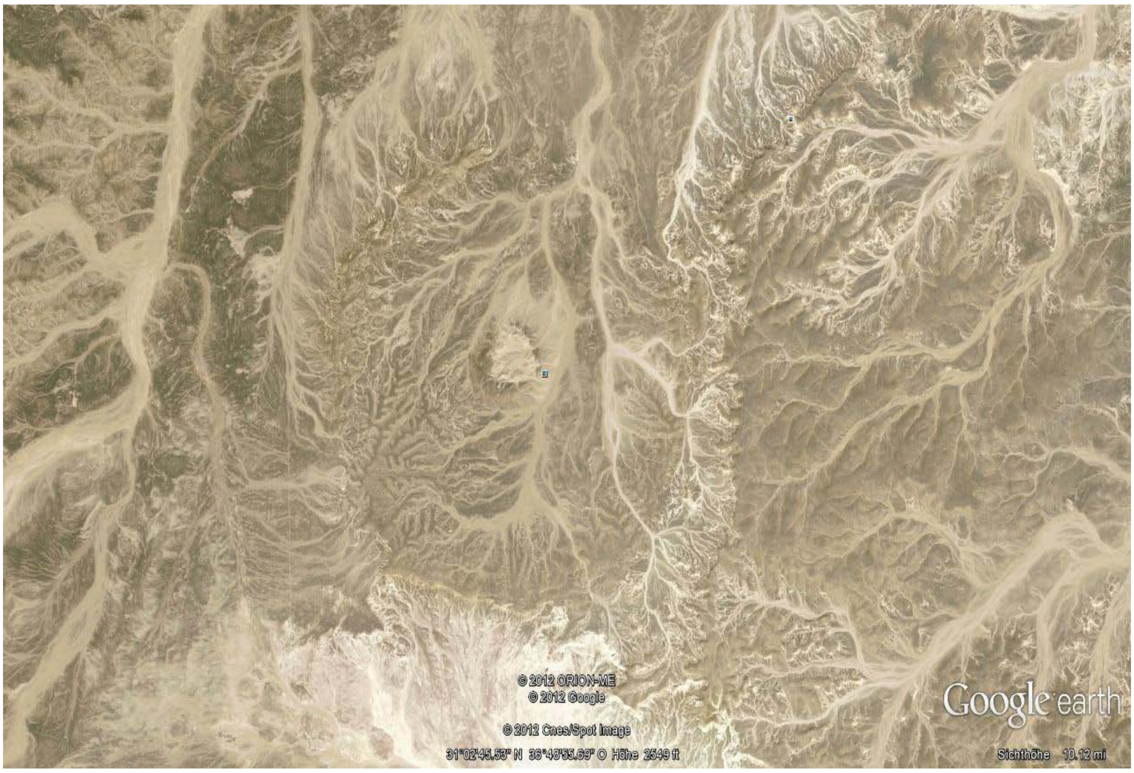

Fig. 121: Meteorite Crater in eastern Jordan seen with Google Earth image (width of about 6 km), margin eroded by gullies connected to a wadi to the east.


Fig. 122: Concretions were baked and thus cracked by the impact of the meteorite.

The silicified limestone commonly have reacted to the shock waves by forming shatter-cones. The extraterrestrial body came with an inclined course so that the impact crater has a somewhat oval shape. It looks as if molten silica from the flint beds has rained down onto the surface of the crater and especially its center. How much of the overburden of the impact crater has been eroded since its formation right after the shock, is not known. Its position in the desert does not allow a simple determination of the age of the impact. The crater lies just to the west of an escarpment formed within the Eocene chalks, was thus definitely formed only after that escarpment had formed. But when that occurred is quite unknown possibly during the pluvial times within the ice ages, and in that case the age of the crater can be assumed to be thousands of years. The net of dry imprinted valleys would indicate a time more wet than today, and in that case it was formed more than 15000 years ago. The southern rim of the crater has been eroded by the gullies leading into the dry valley which connects to the east and into the Sirhan Depression.

The deepened and widened Red Sea communicated with the Indian Ocean through the straits of Bab-el-Mandeb supposedly during Pliocene and only after the Messinian stage. Before, during Miocene salt was deposited in the Red Sea basin. The Bab-el- Mandeb is today 27 km wide with some islands and is only up to 310 m deep. The Gulf of Aqaba has been interpreted to represent a younger phenomenon which was not part of the Red Sea and served during Miocene and Pliocene as erosion channel which drained Arabia. As soon as the Red Sea entered the Gulf, terraces were eroded by the sea into the slopes and the beach was usually accompanied by fringing reefs. At the Jordanian coast up to five terraces can be recognized and the highest of these lies about 75 m above sea level.

The terraces when fully preserved consist of deposits of the beach, the shallow lagoon and the fringing coral reef. The terraces at dry valley outlets are a prominent feature in the southern portion of the Jordanian coast of the Gulf of Aqaba and ancient beach lines can be traced to continue to the south into Saudi Arabia. The terraces exposed next to the Jordanian coast have a slight dip towards the south and near the Royal Diving station not far from the border to Saudi Arabia one of the ancient terraces merges with the modern terrace. Beach terraces have also been found along the southern coast of Sinai and here ages have been determined which are dated to have formed around 110 000 years for the lower terraces, the middle terraces are supposedly 200000-250000 years old and the upper at about 25 m above sea level even older. Similar ages for the fossil shore and fringing reef along the coast south of Aqaba are problematic since here the sediments of the fan into which former shore lines have been eroded and onto which the fringing reefs with their lagoon have been deposited clearly document, that the highest terrace is the one formed last, clearly in altitude above the lower ones and after these had been covered by terrestrial deposits of the fan. The fossil terraces found near the Jordanian shore, thus, have formed in a different sequence with the highest, about 75 m above sea level, produced as the last.

The Gulf of Aqaba may have been dry during the Messinian (late Tertiary) and its history from that time of about 5 Million years ago to the Holocene still needs to be determined. In Pleistocene times when glaciers covered much larger regions around the North and South-pole than today, water level of the oceans periodically took up a position considerably deeper than today, up to approximately 150 m below present level. Since the begin of the Pleistocene about 2.7 Million years ago about twenty cycles of cold and warm climate occurred of which the early cycles were less pronounced than the last four. The warm periods which are intercalated within these four last ice ages had durations of about 10 – 20 thousand years and cold periods lasted a longer time, between 50 - 70 thousand years. Ice ages were named according to their furthest advance to the south in case of the inland ice coming from the North. In northern and central Europe Saale Ice Age at approximately 200 - 125 thousand years ago reached river Saale in central Germany. During the last warm time between 130 000 to 116 000 years ago (Eem Interglacial) and about 230 000 years ago (Holstein Interglacial) sea level rose even higher than it is now. The fixation of much water as ice covering the continents caused the world ocean to drop below its recent level (up to 180 m). During the Eem interglacial the level of the sea rose up to 7 m above modern sea level. The last Weichsel Ice Age lasted from approximately 50 - 15 thousand years ago and ice reached River Weichsel in Poland. So much ice was fixed on the continents during this last ice age that the Mediterranean Sea was separated into two parts connected to each other only by a narrow channel between the Italian Peninsula and Africa. The water bodies of the Mediterranean Sea were thus separated from each other and the water held within them was heated differently. While in the western part it has been reconstructed to around 7°C (today around 22°C), in the eastern part it was warmer with 18°C (today around 26°C).

The last ice age had its climax at about 20000 years ago and glaciers bound so much water in the ice so that sea level dropped 130 to 150 m below that at present time. In the case that all ice held in glaciers were still present today and would melt, sea level would rise by about 50 m. For the past 8000 years sea level gradually approached the current level. During the previous interglacial period when sea level was higher than today also some coral reefs grew in regions now about 3 meters above modern sea level for example along some coastlines in the margins of the Caribbean Sea. These once-submerged reefs and nearby ancient beach deposits indicate that sea level lay for sufficient time at that higher level to allow reefs to grow, and similar evidence of a formerly higher position of the sea level and thus of beach deposits can be observed in many places around the world.

Since the last glacial maximum, about 20 thousand years ago, sea level rose relatively rapidly between 15000 and 8000 years ago at an average rate of 10 mm in each year. The rise of the global sea level was reconstructed to have been from about −50 m between 11000 and 10500 years ago and to about −35 m between 9500 and 9000 years ago. When water of the Mediterranean Sea, for example, reached the level of the Bosporus between Europe and Asia the basin of the Black Sea may have became flooded relatively rapidly and by that displacing many people living on the low lands near the former lake shores that had its level reconstructed to have been at least 50 m deeper than now. This flood may perhaps represent the source or one of the sources of the sin-flood story. The Gulf of Aqaba is connected to the Red Sea by way of the Straits of Tiran which is 13 km wide and its bottom lies at its deepest part 290 m below sea level. The deepest part is near the Sinai shore and the other parts of the straits are much shallower and only about 70 m in depth and have thus been on land in glacial times.

At the Jordanian shore a terrace connected to a fringing coral reef is almost continuously developed, nowadays interrupted by modern construction of the harbor. It is still well developed near the Marine Science Station of Jordan and for some distance to the south of it (Fig. 123). Here usually corals produced a solid reef frame with a steep drop towards the Gulf and a shallow flat lagoon towards the land. This flat terrace with its lagoon was and is produced predominantly by coral growth at its seaward edge and the sediments here consist of coral debris mixed with the carbonate skeletons of all the organisms living here. To it, materials coming from the land are added. Due to the aridity of the land, terrestrial material may have little influence except in places where dry valleys end and occasional flash floods bring debris with them. The beach consists of sand or pebbles and usually has a hard bed near the high tide line consisting of beach rock. In all these zones numerous characteristic animals live of which those producing a calcitic shell are of special importance when the actual conditions are to be compared with those found in the fossil environment.

Fig. 123: The northern side of the dry valley with three of the terraces, the highest lies at the right edge, the lowest at the left edge and the middle is developed with transition from the reef across the lagoon to the beach. The three terraces are separated from each other by fan sediments with angular components. They are exposed due to the erosion of the central valley by subsequent erosion of the fan by later flash floods.

Fig. 124: The lower fossil terrace with reef front forming the steep slope and the pebbles of the beach well preserved next to the slope above the flat of the former lagoon: All covered by fan sediments composed of angular debris forming the steep slope with the next reef and terrace on its top. The middle is taken by the modern valley bottom and the base shows the terrace flat on the other side of the dry valley.

Ancient shore lines and connected to them lagoon and reef sediments were produced on the fan of detritus washed down by occasional rains and floods from the mountains which accompany the coast. The mountains are composed predominantly of the crystalline rocks of Precambrian age and fan sediment consists of mostly angular particles eroded from them, only rarely pebbles consisting of red sandstone occur in a high layer that is at about the position into which the highest terrace has been eroded. The highest of the terraces found on this fan lies at about 75 m above sea level (approximately the left margin of figure (124). Its position, so high up and thus well above a possible former rise of sea level indicates that sea level changes alone cannot be responsiblefor its place on the terrestrial fan. Thus its position is evidence for structural unrest that strongly affected the northern side of the Gulf of Aqaba along the Jordanian coast. On the other side of the gulf at Elat the opposite is observed and the reef and its terrace have gone down within the time that people have inhabited the area. The formation of the fan of debris of erosion occurred predominantly at the time of low level of the oceans during the cold periods of the Pleistocene when weather was more humid and water transported much material from the mountains. While the sea level sank during times of glaciations the climate changed to less arid in Jordan. Within the Weichsel glacial, it rained so much in Jordan that the Dead Sea could expand considerably to form the Lisan Lake. At Bab el Mandeb, at the entrance of the Red Sea from the Indian Ocean, and even more so at the Straits of Tiran at the entrance from the Red Sea to the Gulf of Aqaba sea, ways were even narrower and shallower than they are today, and may even have been closed at times. There exists even a hypothesis that around 60 thousand years ago man could cross from Africa to Arabia by foot.

A fossil terrace represents evidence for a shore environment with pebbles, beach rock, shallow lagoon with calcareous sand and single coral heads, and fringing coral reef with corals connected to each other in dense growth. The sediments which were present on the seaward side of the fringing reef are usually not preserved in the fossil terraces. Of the originally rich fauna of mollusks encountered on the beach, only *Nerita* has become preserved, since it has a thick outer calcitic shell layer. Within the tidal zone large barnacles cover boulders, and have also become preserved (Fig. 125) since their shell is calcitic. From the fauna of the lagoon containing many species of bivalves and gastropods pectinids (*Pecten* and *Spondylus*) some *Lima* and oysters are still found. Most others originally having an aragonitic shell have been dissolved or are present as steinkerns. Sanddollars are present, even though they appear much more delicate than among the Gastropoda the large Trochidae, Strombidae and Muricidae which definitely were present here. At some places with more quartz sand as can be encountered at the beach today, many hermit crabs occur each with a gastropod shell as home. Such assemblages with the thick shells of naticids and strombids as used by hermit crabs are preserved in such a sandy layer and their overgrowths by calcareous algae document that they were used by the crabs after their death. In the actual reef, corals usually have a very rugged preservation, commonly they are predominantly preserved with their filled spaces, while the actual aragonitic skeleton has become rudimentary and is often even crystallized as calcite. The coralline algae in contrast are well preserved, since their original composition is calcitic. Very well preserved are the large spines of regular sea urchins such as of cidarids, but they were completely transformed into single calcite crystals. The echinoderm skeletal elements are usually porous in their structure but their calcite is well ordered, so that during early diagenesis each skeletal element turns into single calcite crystals, well recognized in case of the large spines of *Eucidaris*. Fossil reefs connected to lagoons behind it and also that of the former beach are well preserved just above the road along the shore just south of the Marine Scientific Station of Jordan.

In the case of the reef or parts of it were incorporated in beach rock before becoming part of the terrace, preservation can be better. Here voids between skeletal remains were closed earlier by calcitic cements, better protecting the originally aragonitic structure of the corals from decomposition.

Fig. 125: Fossils from the fossil terraces, sanddollars and naticid and stromid shells that had been carried by hermit crabs indicate sandy beach, a coral slab had been settled by the characteristic barnacles was part of the solidified beach consisting of beach rock.

The deep depression of the Gulf of Aqaba with the shore up to 120 m lower than today absorbed the sediments washed from the mountains to the North. The fan with the fossil beaches and reef, preserved in its lower part, is today totally cut off from its former source in the highlands. The depressions were cut by later occasional rain floods. The head waters of the fan were parasitized by a gorge through which now the road to the harbor was constructed and cut into the crystalline rock north of the fan. Debris washed from the hinterland in the east will now reach the Gulf of Aqaba by way of a different canyon. This situation provides data to the interpretation of the relative time during which the fan of debris formed into which ancient beaches were cut by the Gulf of Aqaba. The beaches were active when the process of sedimentation of the fan was still going on and before dry valleys were cut into it. The beach now lying highest up formed the last deposits that covered the lower fossil reefs with their lagoons (Fig. 126). Thus during the depositions of the last uppermost layers of the fan the beach certainly lay at sea level, but it may be that this level was quite a bit lower than current sea level. In the case that the beach formed during a pluvial period, sea level may have been up to more than 100 m deeper than what it is now. But, the last formed fossil beach lies about 75 m higher than sea level and also higher than any level that could have been reached by the sea at any time of the last 1 million years (fig. 127). Its position is thus a clear indication of much tectonic activity of the area and it documents a considerable movement of the crust north-east of the Marine Science Station for probably more than 100 m since emplacement of the fan. The area has been raised while the bottom of the gulf sank and also swallowed up all the debris that has since washed down the new canyon that was eroded into the fan after its emplacement. Many of the mountains of crystalline material to the east of the harbor and the Marine Science Station had apparently been covered by the large fan and have since been exposed by erosion, representing clear evidence of quite strong uplifting of the north-eastern side of the Gulf (Fig.128).

Since the fossil terraces show a dip towards the south, apparently the northeastern side of the gulf has risen up, while on the western side, at Elat, the area sank. Thus the position of the fossil reef terraces document the rather strong structural motions occurring along the Gulf of Aqaba- Wadi Araba, Dead Sea and Jordan Valley geo-suture structure within geological short times. A connection can exist between the fan of sediment into which the fossil reef were imprinted and the lake that existed in the Disi – Rum area. Water may have flowed along Wadi Imran and across what is now a mountain range between it at the Gulf of Aqaba, picking up some pebbles from a down-faulted block of red “Kurnub” sandstone of Cretaceous age. This runoff extended for about 40 km with level change from about 844 m at Disi Lake high stand to 0 m at Aqaba or less when sea level was lower in a glacial period. (A similar distance is present today from the former lake bottom along Wadi Yutum to Aqaba). The catchment area of Wadi Yutum developed only after Disi Lake stopped draining through its western margin to wadi Araba due to the rising of the shoulders of Araba Graben.

Fig. 126: The lower fan with the terraces recognized as dark lines in the slopes to the ventral wash. The highest beach lies on the ridge eastern margin, the reef area below is documented in the dark line and the dark spots on the opposite hill, and the lower reef is formed by the median plateau. Inclination towards the south is seen in the lower reef documented on both sides of the median fan and the hills next to the road.

Fig. 127: The fan onto which the reefs had grown as in figure 126 were eroded by water coming through a valley that eroded into the crystalline ridge (next to the road). The former coast lines lie near the coastal road, the highest beach on the sharp ridge above the double house and the lowest beach next to the coast road on both sides of the flat wadi base. Construction work has obscured the shape of the terraces while the original fan is seen with recent erosion channels most prominent, but using former channels in general. The pebbles from Early Cretaceous Sandstone can be derived from the mountains just next to the cloud in the eastern side and from Wadi ar Ruwayna area that might have been connected to ancient Wadi Yutum.

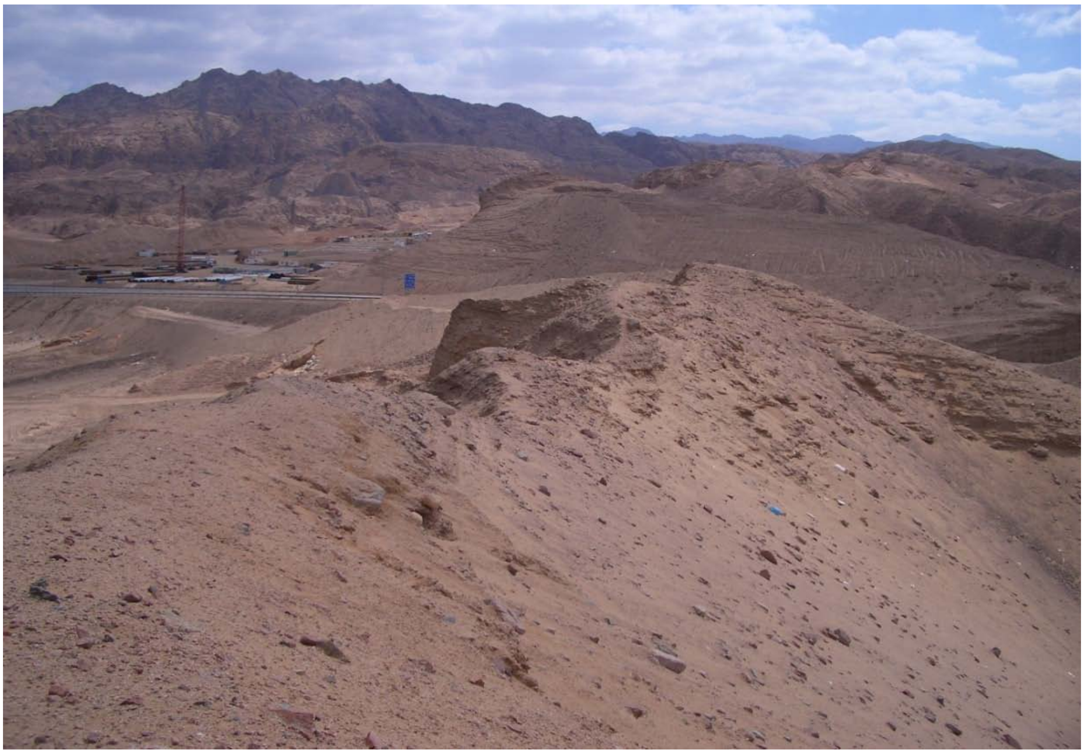

Fig. 128: The same fan as in figure 126 with fossil reefs coming from the mountains on the right corroded and cut by younger erosion channel.

Among the terraces with their reefs three have obviously been formed during distinctly different times. The oldest is the one closest to the road and here a transgressive character is noted with the lower overprinted and partly overgrown by several higher ones. Subsequently higher layers may be fused to each other. They hold the coral ridge, the sediments of the lagoon and the pebbles of the beach with rounded coral debris and the characteristic *Nerita* as indicator fossil. One could split these deposits into several ones on the southern side of the dry valley, while it is one on the northern side. This documents that sea level rose while the terrace formed, but also the mountains were sending down their debris. Because the deposition of the fan was continuous during terrace growth it is difficult to distinguish different stages. Next to former beaches, sometimes sand is intercalated in the fan deposits and within this sand concretions formed which indicate that the sand was coming from the beach and included carbonate particles derived from skeletal elements. This lower terrace is well set off from the median terrace by 10 m of angular fan debris. The exposed median terrace is developed with reef edge, extended lagoon deposits including thickets of branching corals and beach with partly large and well rounded pebbles. The uppermost and youngest terrace has only a beach with rounded pebbles, beach-rock, sand-dunes and a few washed shells. Its zone of rounded beach-worn pebbles overlies a thick fan deposit consisting of angular material and covering the terrace below. The recent base of the wadi has a slightly stronger dip towards the sea than the general dip of the fan and thus the consecutive terraces are exposed at both sides.

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Much information has been compiled by Horowitz 2001

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9. History of people in Jordan

The following is a brief history of Jordan as related to the relevance of water and to the availability of water resources to the different states, kingdoms and communities. The topics of the short history are selected according to the availability of water supply, use of water sources and related climatic changes. None of the kingdoms, or cities had historically been established or had survived, except when an adequate and continuous water source was available. Those are still well visible in areas such as Pella (Tabakat Fahl), Gadara (Um Qais), Gerasa (Jarash), Petra, Philadelphia (Ammon or Amman) and many others with less spectacular remains. They were only to be established and in part continue existing because of the availability and wise use of water.

In Jordan 90% of the country is semi arid and thus devoid of perennial water sources. This climatic situation is found in the whole arid Middle East with short rainy seasons and high rates of evaporating water. In regard to its vegetation Jordan has three geographic areas, one is with plants of Mediterranean character on the high eastern edge to the Jordan rift, another lies in the Jordan rift with the Jordan River in its northern portion and the Araba Valley south of the Dead Sea with flora as in the hot dry areas of Africa (Sudanian) and a third occupies the desert regions to the east and south with the characters of the Arabian desert. These three geographic areas grade into each other via transition zones; from the highlands into the Jordan Valley where it may locally be almost tropical warm and to the desert region. The Mediterranean region was originally largely wooded, especially by oak and pine trees in the north and oak and juniper in the south. These trees were of great importance to the population, and were used for construction and as firewood; they thus have largely disappeared through times with the exception of parts of the Ajlun Mountains in the North.

The first people entering the scene within the Pleistocene were hunters following predominantly large animals which represented their game. Along their way, they also collected roots, fruits and seeds from wild plants. They stayed near water and migrated between pastures as did the animals they hunted. The presence of these early people can be well recognized especially at places of their rest, since they fabricated tools for hunting and for cutting the meat of their prey. In Jordan these tools were commonly made of flint and their shape changed with time, from relatively coarse implements of the more ancient hunters to instruments of finer fabric in later times. These tools thus allow the recognition of a relative time range in which they were produced. Accordingly, humans were present in the region throughout the last million years. Simple pebble tools were found in Ubeidiya Formation of approximately 1.4 million years, possibly made by *Homo erectus* according to the bones of the accompanying fauna. The skull of *Homo erectus* was discovered in a cave in Lebanon and is approximately 150 thousand years old. Modern man, *Homo sapiens,* appeared in the region at least 50 thousand years ago and also the Neandertaler subspecies was living here, obviously earlier and also when modern man came to the region on his way to Eurasia as can be recognized from human bones found in Levantine caves.

The economy of a Paleolithic society (people of the Old Stone Age) was that of hunter gatherers. Humans hunted wild animals for meat and gathered food, firewood, and materials for their tools, clothes, or shelters. Human population density was very low and life - style nomadic. Hand axes of lower Paleolithic style were found for example about 12 km to the east of Azraq in al-Dahikiya, where people periodically housed near the shore of a lake that existed here during pluvial times. Here they had their hunting station on a fan of sediment that had been washed from the east into the lake, and here they also produced their tools. The lake shores during Pleistocene times were also frequented by large animals most of them ancestral to those that occupy the East African savannah today. Most of the eastern part of Jordan is covered at the surface by chert (flint) that has been eroded from the limestones and chalks here exposed and served as a source rocks for tools and implements. The chert beds intercalated in Paleogene chalks and the Late Cretaceous chalks and limestones made the hunter gatherer life easier by providing fitting material for tool production.

Azraq and Al-Jafr Basin represent nodes on a chain of ancient lakes that stretched from northwestern Saudi Arabia to northeastern Syria during the wetter times of the Ice Age (Pleistocene). In times when ice was covering much of northern Europe the climate in Jordan was often considerably wetter than today and the open plains between shallow lakes were ideal for hunting by *Homo erectus*. The sites have yielded many of heavy-duty butchering tools chipped from local deposits of flint. The tools are cleavers, a form of hand-axe that could be sharpened anew by striking flakes from the cutting edge. Animals such as elephants, rhinos, horses (wild donkey), gazelle and ostrich live in the steppe and were hunted when they came to the water to drink. The lake at Azraq during the Pleistocene pluvial period covered up to 600 square kilometers, with a zone of reeds on its margin and trees near the shore. It was a quiet lake with about 500 m above sea level in its center and here with organic sediments deposited. Coarse sediment is present in fans only near the mouths of wadis entering the lake and documenting that its shores were of low relief. Further to the west of the Azraq basin a wedge of debris had been washed from the large fields of volcanic rock which continue to Jebel Druz area that is up to 1500 m above sea level in the northwest. Here the continued volcanic activity produced so much new rock material that during rainy periods, large fans of debris formed. They eventually separated the Azraq Lake from its former outflow to the west along Wadi Dhuleil and from its connection to River Zerqa. The dividing fan has been interpreted to have come into existence during the later phase of Lake Lisan that occupied much of the former Jordan Valley joining almost with Lake Tiberias.

Until about 15000 years ago Lake Lisan occupied most of the northern Jordan Rift Valley and reached from the region just south of Lake Tiberias to around 45 km further south of the modern Dead Sea. Lake Lisan existed for about 50000 years and the surface of the Jordan Valley, to a large extent, represents the former bottom of the Lisan Lake. Before that the area was flooded by the salty Lake Lisan. River Jordan had meandered on the floor of the rift valley and pebble fans from the rivers and creeks issuing from the eastern slopes reached the ancient river course. These fans are now again excavated by the extant River Jordan that has eroded the Zor into the former Lake bottom cutting through lake deposits to about the same level as it had before the formation of Lake Lisan. The Zor thus represents a distinct central valley with steep sides that were eroded into the bottom of the Jordan Valley.

Just to the west of the town Mashara the deposits which formed there when Lake Lisan transgressed over sand and gravel of former Jordan River are now exposed. Here, sand had been deposited by the river during the approach of the Lake and turned into ground of a swamp with roots and coaly deposits still to be seen. The swamp was than flooded by the salty lake and the characteristically laminated lake deposits formed on top of it. At other places, further to the south, also clay washed into the lake and deposited onto the sandy sediments of the former river bed when the lake had reached that area of the valley. It had come as fine suspension with flood water from the highland and settled in the standing water of the salty lake without disturbance of bottom life. These deposits are now exposed on the slopes of the Zor at the margin of the modern central valley of the Jordan River. They are evidence of the relatively similar position of the valley floor from the time before the formation of Lake Lisan more than 50000 years ago to its modern position. But as a difference to the conditions to those before formation of the Lisan Lake to the situation as it is now the creeks and small rivers coming from the eastern side of the rift carried so much water that the gravel transported by them was washed directly to the Jordan River. Today the gravel fans end closer to the slope of the rift. Tributary creeks in contrast have eroded into the sediments of the former lake bottom but here no longer have sufficiently strong currents to carry coarser material. Exceptions are rivers such as the Yarmouk and Zerqa. Apparently, the smaller streams transport nowadays less water from the eastern Highlands than was the case more than 50000 years ago. The watershed at some time in the Holocene was thus extending further in the east than at present and catchment areas were more extensive. They have since moved to the west, and water remained in the huge depression consisting of the Azraq – Sirhan - Jafr troughs.

Since the decline of the Lisan Lake to form the Dead Sea within the last 15000 years water level has gone down by about 200 m and therefore the valleys cutting into the escarpment are still being eroded. Lake Lisan occupied much of the Jordan Rift Valley, and people lived next to its beaches at places where fresh water of springs, creeks and rivers existed. Flint implements used by them are of a fine fabric, giving evidence of their manufacturing during the last part of the stone-age, the Neolithic time. Among other tools fine arrow heads and spear heads were fabricated and used by the hunters. Still during the era of the Stone Age in Jordan the Lisan Lake began to shrink in size around 20000 years ago until reaching the size of about the modern Dead Sea (around 400 m below sea level) at around 16000 years ago. During this time man changed his habits from food – gathering and hunting to food production and domestication of house animals. Neolithic men remained in one and the same place, and thus constructed permanent houses and changed their surroundings to grow crop and keep animals. People were obliged to develop special techniques to survive during all seasons of the year in the same place. This change occurred in Jordan around 10000 years ago within the Late Stone Age. People used stone implements and had not invented the production of pottery at that time. But even before having burned clay pots food was roasted and cooked which made it more digestible. The development of permanent settlements and villages must have dictated a change in social structures, which in turn lead to political interest groups.

On the eastern margin of the Jordan valley at the former highest shore of Lake Lisan, and three kilometers to the north of the main mound (tell) of the ancient city of Pella lies Wadi Hammeh. Here a series of sites was discovered and one with a group of circular houses each of over ten meters in diameter representing an ancient village. Nomadic people living as hunters and gatherers had become urban dwellers. Excavations documented that much of the food still came from hunting, and these early village dwellers relied more and more on the wild grains of the region for their food, and finally they produced the grains planting them and thus began with agriculture. This revolution of the human society occurred at a time probably before domestication of food animals. According to archaeological data, the houses of the village at Wadi Hammeh had stone foundations and the upper part of the walls and the roof were constructed of wood. Tools were made of flint, mortars and pestles of basalt and alongside limestone carvings and bone sickles were found. Beneath the floors of the houses were burials with marine shells on strings around the head and each skeleton had a large stone placed on it. Excavators found that the village at Wadi Hammeh was suddenly abandoned. Pestles still rested inside mortars and a complete sickle lay abandoned in the centre of a house and the place was sealed in time for over twelve thousand years. Today a small village lies at the end of Wadi Hammeh which has its main spring in the steep valley in a small house with a bath basin and with the water having sulfide smell.

In Jordan water and irrigation engineering can be documented to have occurred at about the same time when it also began in Mesopotamia where water of both the Euphrates and the Tigris Rivers was utilized and also in Egypt where the Nile water was used for irrigation. Most ancient settlements in Jordan had a natural source of water, but of much smaller size than that in Mesopotamia and along the Nile. In the Neolithic Ain Ghazal village that lies in the eastern outskirts of modern Amman, people used spring water and water of the clean Zerqa River near to its springs. They planted crops on prepared fields, watered them, and kept house animals. These early Jordanians cultivated barley and ancient species of wheat, legumes such as peas, beans and lentils and chickpeas in fields above the village, and herded domesticated sheep, goats and pigs, and later also cattle. The population lived at the same site all the year and practiced a combination of subsistence farming and hunting deer, gazelle, horses (wild ass), pigs and smaller mammals such as fox or hare.

Ain Ghazal village existed continuously for about 2000 years and dates as far back as 9300 years ago. Ain Ghazal village represents one of the largest known prehistoric settlements in the Near East. It was set on terraced ground at a valley-side, and was built with rectangular mud-brick houses that accommodated a square main room and a smaller anteroom. Walls were plastered with mud on the outside, and with lime plaster inside that was renewed every few years. The source of this material is found nearby in the chalky Ain Ghazal Formation. The excavations suggested that approximately 3000 people inhabited the village, which is a higher population compared with contemporary Jericho on the western side of the Jordan, and is also more than the population that lived in Wadi Hammeh. Artistic people of Ain Ghazal produced statues which are half-size human figures 35 to 100 cm high and modeled in white plaster around a core of bundled twigs. The figures have painted clothes, hair, and in some cases, ornamental tattoos or body paint. Based on carbon-14 analyses of charcoal found in association with the statues their age could be determined as around 8760 years ago. All faces of the statues exhibit large eyes set far apart and outlined with black bitumen, representing images of the most ancient Jordanians which lived approximately 9000 years ago. Color was added with ground copper ore that was collected from Wadi Faynan in the South of Jordan as documented by metallurgical analysis.

Ain Ghazal village, in its long existence near the head-water of the river Zerqa relied on the continuously flowing spring that represented a secure source of good water. At Ain Ghazal a shift from a broad-based economy with a reliance on agriculture to one largely based on the exploitation of a few species of domestic animals, especially goats has been reconstructed. This may explain the end of the Neolithic village in a catastrophic flood that left a layer of coarse rubble, onto which no new settlement was founded. Too many goats may have destroyed the plant cover of the region in which they grazed throughout the year and exceptionally strong rain may have washed off the soil in a single, final flood produced by strong rain. The early farmers of Ain Ghazal may thus have transformed themselves into goat dependent society that took up nomadic life to survive.

But this most important River Zerqa in Jordan was later also the main water supply for Amman – Philadelphia, founded not far away somewhat upstream. At the mouth of the Zerqa River, in a fertile triangle near modern Deir Alla, several archaeological sites indicate that the water was of good quality near its confluence with Jordan River, quite in contrast to modern times, in which this river serves as the main runoff of sewage effluents of the cities of Amman, Zerqa and Ruseifa in addition to the different types of industries.

In the South of Jordan Neolithic villages existed near Petra, one with fields around it on flat alluvial soil at Beida and the other on a rocky ledge next to a steep sided valley cut in the Cambrian Sandstones called Ba’ja. Both are pre-pottery Neolithic villages which existed for a few hundred years, 7000 to 6600 years ago. The People of Beida grew barley and wheat and probably watered some fields from a creek, and collected water by constructing earth dams in the canyon below the narrow village. Here water coming periodically during winter is collected behind the dam and used as drinking water in the dry seasons.

Pottery of the so called Yarmukian period that lasted from 8400 to 7800 years B.P. has been found in Ain Ghazal and also near Lake Tiberias, here produced in a small village near Sha'ar Hagolan that lies next to the Yarmouk River. From the Dead Sea terraces and pollen in the sediments of the lake it has been reconstructed that the climate changed to somewhat drier around that time to improve again a few hundred year later. The people of Sha'ar Hagolan about 8400-8000 years ago owned domesticated animals such as cattle, pigs and dogs, herded sheep and goats and hunted wild animals among them much fowl and fish. They also cultivated olives (*Olea europaea*), dates (*Phoenix dactylifera*) and perhaps also pomegranates (*Punica grantum*), besides produced pots and made small figurines of animals and fat little ladies. They collected their drinking water from a constructed well, distinct from the river water. To do this they dug a four meters deep and 2 m wide pit that penetrated the soil, a gravel bed and the underlying lacustrine marly clay of Lisan Formation to reach the water table in a gravel bed. A central shaft was held stable with a lining of larger stones. This Neolithic people thus utilized water that was filtered by the sediment and was of high quality even though water of the river Yarmouk was available nearby. Around 7000 years ago, at the end of the Neolithic period, the level of the Dead Sea as has been reconstructed based on beach deposits and preserved salt crusts on the shell of land snails that lay 120 m above the sub-modern level of about 400 m below sea level. That would have resulted in an extension of the Dead Sea for approximately 40 km to the north reaching the area of Karama. But afterwards the level of the Dead Sea dropped to lower level as it is now and a layer of salt was intercalated in Dead Sea mud.

During the Chalcolithic age representing the Copper/Stone Age, people learned to smelt copper and the metal age was born. This copper age is considered to have lasted from approximately 6500 to 5500 years ago. In Jordan climate may have improved somewhat during that time since sea level of the Dead Sea rose around 5600 years ago so much that the sill west of Lisan Peninsula was flooded. During transition from the stone age to the copper age people in Jordan began mining ore on both sides of Wadi Araba, at Wadi Faynan some 30 km south of the Dead Sea on the eastern side of the Jordan Dead Sea - Jordan Rift and at Wadi Timna on it western side about 15 km north of Aqaba. Copper ore consists of mineral nodules which formed along the former interface of the Precambrian rocks to the Cambrian sandstone and in the limestone layers above (Burj Limestone) in the areas where volcanic material forms the base. In both Faynan and Timna archaeological excavations have revealed that the ore was discovered as early as 7000 years ago, in the Neolithic period, but the ore was used at first for ornamental purposes. Copper metal was later produced from it, also derived from the marginal mountains of Wadi Araba and was traded for example to Egypt and used there even before the begin of the Old Dynasty around 4700 years ago. A mining town was excavated in Wadi Faynan called Khirbat Hamra Idfan that had a large metal workshop which was destroyed by an earthquake still before 4200 years ago, during the Bronze Age and in its ruins preserved tools for and objects of copper production.

The city of Tall el-Hammam was founded at the southern end of the perennial confluence of Wadi Kafrein, with Wadi Hisban a few hundred meters to the south, and existed from 5600 to 3550 years ago during the Bronze Age. The city had at least two springs located inside the city walls one with warm mineral water and the other with cold fresh water. The shore of the Dead Sea laid well to the south and the broad delta of the Jordan River was not far away. About 500 years before the city was founded the water level of the Dead Sea was reconstructed to have been higher due to a wet climate with a maximum at about 5600 years ago. From burial sites near Ghor Safi, which were used at about 6000 years ago, it was determined that the lake level of the southern Dead Sea was below 340 m below sea level. Around 5000 years ago much charcoal from the city deposits documents the presence of ample wood, later charcoal becomes more scarce, indicating that people had used up fire wood to a large extend, and later used dried dung for cooking fire. Bones give evidence for the presence of cattle, sheep and goat as house held animals along with gazelle that were hunted. Planted crops were cereals, mainly wheat. Also olives and figs (*Ficus carica*) were harvested and eaten. The city debris piled on top of each other and thus producing Tall el-Hammam. It represented the center of a kingdom that dominated the southern Jordan Valley and existed for nearly 1500 years. Disruptions in the relative peace of the region are evident since the inhabitants of Tall el-Hammam constructed a defensive system of a stone and mud-brick wall of 2.5 km length around the city. That wall was more than 5 m thick and up to 15 m high. At 2700 BD an earthquake shattered the wall and it was repaired and served for another 900 years until an even larger wall was build on top of it around 1800 BD. At similar time also in the city of Pella a wall was enforced as well. During each flood season in spring, the Jordan River overflowed its banks north of its mouth at the northern end of the Dead Sea, providing a wide-spreading inundation. Farmers from the Tall el-Hammam city utilized the annual flood by planting crops in the fresh alluvial silt deposits. With so many reliable sources of water, the kingdom of which the name is unknown flourished with up to three harvests each year in its below-sea-level sub-tropical environment. It continued and flourished through the catastrophic changes of the climate that has been reconstructed to have affected the area around 4000 - 4250 years ago. During this period the level of the Dead Sea was reconstructed to have dropped by about 100 m and the fertile lands in Mesopotamia were interpreted to have partly been turned into deserts forcing the people living there to emigrate.

In northern Jordan in the town that has formed Tall Zira’a since 5200 years ago, almost on top of the slope of Wadi al-Arab, a decline of town life was noted to have occurred at the end of the Early Bronze Age and the town grew again in the Middle Bronze age and had a wall built around it in Late Bronze Age. Tall Zira’a has an artesian spring in its center that provided water to the settlement as a result of a natural siphon phenomenon leading the underground flow of the water from the higher level of the hills. The crisis within the Bronze Age that is probably related to a drastic drop in precipitation is documented around 4200 years ago, also from Egypt which led to the collapse of the Old Kingdom followed by decades of famine and strife. With the aid of stable isotopes in wood of a *Tamarix* from 2265-1930 BD rainfall variations were reconstructed and a record of a succession of prominent droughts at approximately 2020 BD and a longer one 1930 BD were documented, which agrees with analysis of the pollen spectrum that were carried out from sediments from the Dead Sea.

In the west Jericho, in the north Deir Alla, Pella, Scythopolis, and Rabbath-Ammon, Tall al-Umayri, and Nebo in the east continued into Late Bronze Age while the kingdom with its center at Tall el-Hamman ended 1550 BD due to unknown reasons. At about this time the Egyptians of the New Kingdom conquered the region which they called Canaan, predominantly, the area to the west of the Jordan.

At the Chalcolithic and early Bronze Age (4–3rd millennium BD) the city of Jawa also called the lost city of the Black Desert was growing. It is a relatively large settlement located on the basalt plateau desert of Harrat Ash- Shaam, within the Jordanian part of the north Arabian Desert. People here built sophisticated run - off collection systems for water storage. One of the oldest known dams of 5.5 m in height stands in Jawa and was constructed to collect water. The city was built between the sown land and the desert (Fig. 129). Upstream of Jawa the south-eastern flanks of the Hauran (Jebel Druze) represent the source of water that runs via Wadi Rajil into the Azraq basin. In the vicinity of Jawa, no springs or perennial streams are found today. Also no shallow ground water aquifer exists that could be reached by wells. Jawa depended mainly on its elaborated systems of runoff control by canals and dams and water storage and the ancient systems allowed the city to thrive even though the climate was not considerably more humid than today, but it may have been the wettest period in historical time.

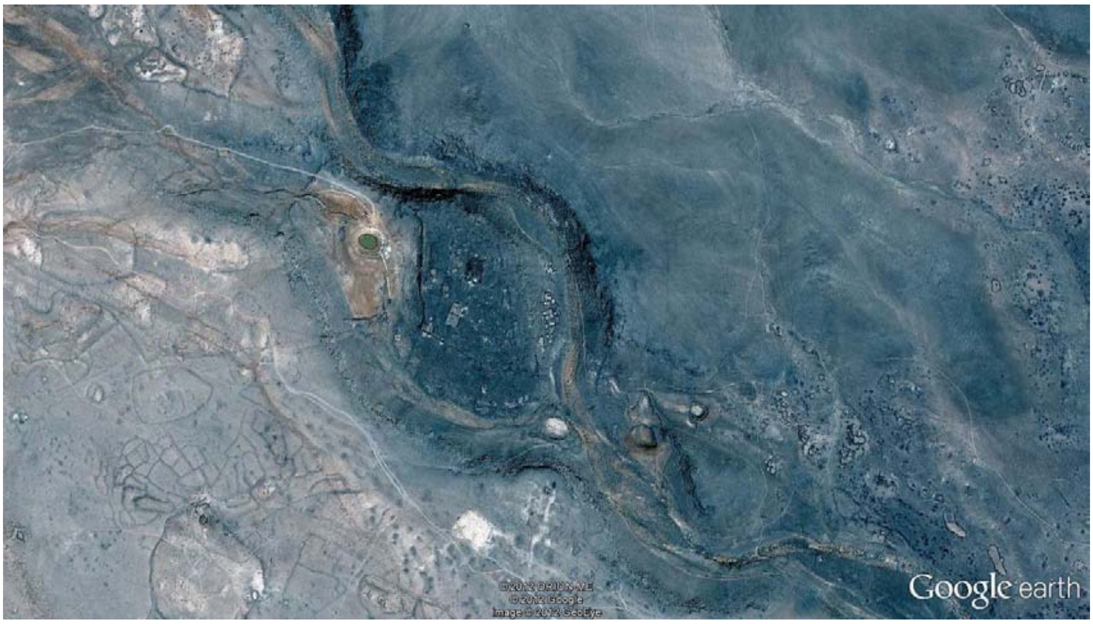

Fig. 129: Ancient city of Jawa as in Google Earth

During the Early Bronze Age 5200 to 3960 years ago many settlements were established in various parts of Jordan, both in the Jordan Valley and on the highlands to the east of it. Many of the villages were surrounded by defensive fortification to protect the inhabitants from neighbors or perhaps marauding nomadic tribes. Channels were constructed to provide fields and town with water. Burial customs developed as those of Bab al-Dhra at the NE of Wadi Araba where over 20 000 shaft tombs with several chambers that may have contained more than 200 000 corpses have been preserved documenting that the area was well settled. Also graves composed of mud bricks to hold the bones along with pottery, jewelry and weapons were constructed. And, at other times hundreds of dolmens were erected of large stones set to form a chamber, for example near Tal al- Hammam during late Chalcolithic and early Bronze times. Changes in burial customs may well indicate that new people came into the area, but also indicate that a new religion spread bringing with it different burial rites.

In a depression in the hills above the modern town Mashara in the Jordan Valley the strong spring, Ain al Jirm, used to be the source for a creek in which not long ago a rich fauna of *Melanopsis* and *Theodoxus* lived. This spring has since been destroyed by a modern pumping station that was constructed to collect the water for drinking purposes, but has since over-exploited the groundwater which subsequently turned salty. The spring served as the central water supply to ancient Pella that existed as town since about 5000 years ago. Ain al Jirm emptied into Wadi Jirm with formerly rich gardens at its sides. The scene was illustrated on a Roman coin that was minted at Pella in 183/84 AD at the time of the Roman emperor Commodus and again 217 AD by Caracalla. It shows a temple accompanied by terraces and buildings.

Pella (Tabaqat Fahl) was founded in Neolithic time when agriculture was well established and domesticated animals were kept. The steady stream produced by Ain al Jirm allowed agriculture along the wadi and in the Jordan Valley. Olive oil was pressed and kept in flasks. Also large grain storage bins were used. The inhabitants of Pella obviously organized the use of this water and produced a surplus of food. During the early Bronze Age, grapes (*Vitis vinifera*) were planted and vine produced. The main mound of Pella was surrounded by a city wall of stone and mud-brick which indicates the need for defense and the city may have had around 2000 inhabitants. A similar defense system was constructed around the city at Tel al-Hammam approximately at the same time, apparently also at Megiddo in northern Israel, which is an indication for regional wars among the different city states in the Jordan Valley area or the appearance of intruders from further away.

During the Middle Bronze Age approximately 3900 years ago, Pella reached a peak of wealth and size. From a Middle Bronze age tomb many objects such as gold earrings, copper bracelets, and pottery and alabaster vessels were excavated. A large Bronze Age temple was reconstructed 3660 years ago repairing a more ancient site with earthquake damage. One of the Late Bronze Age leaders of Pella was even mentioned by his name as king of the place in the Egyptian Amarna Letters, and the town was called Pehel, which only later in Hellenistic time changed to Pella.

Many of the fortified hilltop towns, between 4300 to 3950 years ago, were recognized in archaeological analysis to have been abandoned for unknown reasons. Possibly that was due to earthquake destructions or to a sharp change in the climatic conditions. A sea level drop at the Dead Sea has been reconstructed for about that time and later with a top level 3500 years ago, and at about this period, the catastrophic volcanic eruption of Santorin (Thera) in the Greek Archipelago at 3630 years ago is reported. Also people from Asia Minor known as Hyksos/Hittites at 3700-3650 or Hurrians/Mitanni 3400 years ago crossed the Levant and may partly have reached Jordan on their way from the Northern Levant to Egypt.

The Egyptians had established their administrative center from the 15th to the 12th century BD not far from Pella in the town called Scythopolis in Hellenistic time (now Beit She'an). Near it they fought the Battle of Megiddo 1468 BD which resulted in the conquest of Canaan which they held under their control for 350 years. Scythopolis housed the Egyptian imperial administration in northern Canaan (Levantine area between the River Jordan and the Mediterranean Sea) and were frequently mentioned in Egyptian documents of the New Kingdom. In a central fortified palace of Scythopolis which otherwise was without city wall the Egyptian governor lived as well as the families of the Egyptian officials and it also held the granary. From inscriptions on basalt steles several victories over the Canaanite cities, which rebelled against Egyptian domination were recognized. Water supplies of the city came from springs in its vicinity. Grapes were widely cultivated and vine produced as is documented by the abundance of the pollen-grains of *Vitis* extracted from lake sediments that were dated to be deposited in the 11th and 12th century BD.

The decline of Egyptian control over Canaan is connected to invasions by a number of mysterious people coming from the North (Sea People) around 3200 years ago. The end of Egyptian copper mining in the Araba Valley at Timna falls together with wars which affected the whole area and were brought into connection to the mysterious Sea People, who also overran Egypt and must have been a problem in Jordan as well. Their appearance at the begin of the Iron Age is connected with great upheavals throughout the eastern Mediterranean with the Mycenaean civilization of Greece collapsing as did the Hittite Empire centered in present day Turkey. The town of Tall Zira'a in northern Jordan was destroyed during these invasions as well as much the larger ancient Hazor near Lake Tiberias, a town that was reconstructed to have had about 30000 inhabitants in the bloom time of the country of Canaan. The involvement of the newly formed state of Israel in the destruction of Hazor is also discussed.

As a reaction to the aggressive invasions by intruders to the area, the people of Pella constructed thick walls around their town. But excavations revealed that the inhabitants of the city of Pella were continuously doing well and even built a new temple on the same spot as the earlier Middle Bronze Age temple. Next to the temple a building contained over 20 rooms for storage, some with vessels for holding liquids such as oil or wine and others with baskets still containing the remains of chick-peas. Other rooms were devoted to cloth weaving, which represents a major economic activity of the time. It has been suggested that at Pella horse drawn chariots of wood were constructed and sold as well as the horses to pull them were bred. Thus Pella could have made profitable business with its neighbors. In near-by Scythopolis a mixed population of Canaanites and descendants of Egyptians and Philistines built temples on the ruins of the earlier Egyptian temple.

Around 3200 years ago many of the Near Eastern and Mediterranean kingdoms collapsed and one of the groups of Sea Peoples which came from the Aegean region were the Philistines which settled on the southern coast of Canaan. Philistine towns along the Mediterranean shore are Ashkelon, Ashdod, Ekron and Gaza and here a characteristic pottery of the Mykaenean style (ancient Greek) was produced. The houses excavated in Ekron have the construction that was characteristic to houses of Aegean people of the time. The Philistines who were the name givers for Palestine came into conflict with the people that had, as uniting factor, the monotheistic religion of the Jews with centers at Jerusalem and Samaria. Scythopolis was burned to the ground at the beginning of the 10th century BD probably by these Israelites. In contrast the town on Tall Zira'a began to grow again and by 3000 years ago constructed a wall around it, but the people settling here had changed from relying more on trade, as was the case in the Bronze Age, to living from the land during the Iron Age.

By the early Iron Age, the southern Levant came to be dominated by the kingdoms of Israel and Judah, besides the Philistine city-states on the Mediterranean coast, while in Jordan the kingdoms Edom to the south of Moab and Ammon in the center and Aram-Damascus in the North developed and all of these had periodic conflict with each other. The northern Levant was divided into various petty kingdoms among them Phoenician city-states. All these small states, each with a dominating larger town, were engaged in struggles with each other at certain periods.

The Ammonites had their domain, during the Iron Age from the spring of River Zerqa and along its course to its mouth in the Jordan Valley in Deir Alla to the area around Madaba. This became later a vassal state of the Assyrians. Their capital was in the citadel of Amman. At Deir Alla an inscription was found in an excavation revealing a many-chambered structure that was also destroyed by an earthquake. On the wall was written a prophecy by the priest and prophet Bala'am. The inscription was written in a peripheral local dialect with Aramaic and South Canaanite characteristics and is datable to ca. 840-760 BD. Near Deir Alla in a small village at the mouth of Zerqa River into the Jordan Valley plain an iron bloomer (smeltering oven) has been excavated. Here the iron ore as it occurs in some layers of the Jurassic outcrops just upriver was mixed with charcoal and in a clay oven transformed into metallic iron. C14 dating carried out on charcoal proved that this was done approximately 2940 years ago. The dry iron ore was mixed with about the same amount of charcoal and in a clay oven, with pipes at the bottom providing the air, heated and transformed. The result of the heating process is a material containing much metallic iron which is further enriched by hammering.

The Kingdom of Moab existent between 1000 – 800 BD covered the center of Jordan, and its capital cities were at Karak and Thieban. The famous Moabite Stone of King

Mesha set up about 840 BD documents that he had two reservoirs constructed in the midst of Karak since there was no cistern in the city. He also obliged all people to build cisterns in their houses, an advice that could also be obliged to at modern times. During archaeological excavations, nearly 100 cisterns were found on the site of Dibon (Thieban) and in the surrounding area. The people of Moab lived east of the Dead Sea and in the traditional account of history fought with Israel but retained their independence. They were eventually conquered by Assyria in the 8th century BD, and then partly exterminated by Babylon in the 6th century BD. In Assyrian written records it was stated that the Moabites had some problems with marauding nomads coming from the deserts of Arabia. The destruction of Moabite towns in the 7th and 6th century BD may have been due to neglect which enabled the desert nomads to enter formerly settled land.

The Iron Age Kingdom Edom occupied an area south of Wadi Hasa and included the Wadi Araba and Petra. The Edomite capital was Buseira on the highland, 22 km south of Tafila and it was probably also destroyed by the Babylonians (Neo- Assyrians). Edomites were skilled in copper mining and smelting in the Northern Araba with connections to Aqaba. The copper ore district of Faynan is located ca. 40 km south of the Dead Sea and ca. 130 km north of the Gulf of Aqaba, along the eastern margin of Araba Valley and in the foothills of the Jordanian plateau. Export of copper products from the mining and smelting areas was based on caravans of camels and donkeys that traversed the desert towards the coast of the Mediterranean Sea, or the northern states along the Kings Highway on the Jordanian Plateau. The camel had been domesticated during the last centuries of the 2000 BD and appears in the southern Levant during early Iron Age or somewhat earlier.

The Faynan district provides evidence for the history of copper exploitation and production throughout most the Iron Age (ca. 3200 – 2500 years ago). The smelting sites in Faynan are located in a short distance from the mines and the location for smelting operations was connected to the availability of water and associated plants. Fuel for Iron Age smelting consisted predominantly of plants that grow in oases and were either used with their wood or after having been transformed into charcoal. A similar type of copper production as that of the Bronze Age was carried out until about 926 BD. The analysis of the waste material documents that intensity of production increased with time. The production system at approximately 1140 – 1000 BD, according to the archaeological interpretation, was large-scale, full-time operation that included the employment of a large labor force. A military campaign of Pharaoh Shoshenq I to the area (927 BD) is described on the walls at the temple of Karnak at Thebes. After it, a better technology was introduced that may well have been derived from Egypt. The Iron Age copper production in the Araba Valley represents the most extensive copper production in this region in history, larger than in the Roman-Byzantine period.

In the Early Bronze Age the most common sources of fuel for the smeltering process were juniper trees from the woodlands on the slopes of the Jordanian plateau and

Acacia from the neighborhood of mines. During the Iron Age, shrubs were the primary source of fuel primarily *Tamarix*. In the Roman period again *Acacia* was used as a fuel source, together with the local shrubs. In the Ayyubid/Mamluk period *Quercus* of the woodlands of the slopes was exploited. These differences appear unrelated to the climate which was more or less as at present, but may have had some unknown cultural reasons.

The entire region, was conquered by the Neo- Assyrian Empire during the 10th and 9th centuries BD, and remained under Assyrian control until the end of the 7th century BD. Ammon, Moab and Edom had to pay tribute to the Assyrians while Scythopolis was destroyed to its foundations by Tiglath Pileser III of Assyria, when he conquered Israel in 732 BD. The Assyrian Empire ended in 612 BD, and in its place arose the Babylonian Empire and the resulting wars caused considerable population shifts, for example the migration of the Edomites from Jordan to the part of their country on the western side of the Jordan, later called Idumaea with its center at Hebron. Nomadic tribes increased their influence in southern Jordan as fortified cities were deserted.

In 587 BD the Assyrian-Babylonians destroyed Jerusalem and deported thousands of Jews to Mesopotamia and quite possibly also deported people from other towns of the region. Assyrian raids in the North of Jordan destroyed for example the town of Zira'a. The Persians under Cyrus II in 539 BD ended the rule of the Babylonian Empire and their empire became the largest yet known in the Near East ranging from Egypt to India. Jordan and Canaan were Persian until the Persian Empire ended with the conquest of the Middle East by Alexander the Great in 333—332 BD. The data from the Dead Sea level at that time, ranging from about 2500 years ago, indicate a relatively low level of water, thus dry climate. Pollen in the deposits of the Dead Sea of that time include at first many pollen from olive trees and of *Phoenix* (date palm), later more pollen are derived from pine and oak trees, which indicates a reforestation of the surrounding lands and thus less influence on the vegetation by people which can be interpreted to fewer farmers living in Jordan at that time.

The arrival of Alexander bought Pella region under strong influence of Greek, or Hellenistic, culture. At this time the city received its name Pella since its ancient name mentined in Egyptian texts resembled that of the town of the birthplace of Alexander the Great in Pella in Macedonia. Many characteristic objects of the Hellenistic period were found, such as lamps from Athens. Bowls, coins, glass and statue fragments indicate that under Hellenistic dominance Pella became prosperous again, as did the region evidenced by pollen of *Vitis* and *Olea* found in lake deposits. After Alexander died in Babylon in 323 BD, Pella region fell under the control of his general Ptolemy who also ruled southern Syria and Egypt from Alexandria. In 198 BD the other Hellenistic dynasty of the Seleucids annexed Pella region and ruled it from Antiochia on the Mediterranean coast (NW Syria).

Hellenistic influence is also noted in the construction of Iraq al-Amir situated on the west bank of the Wadi es Sir about 4 km upstream from its confluence with Wadi

Kafrein and just to the west of Amman. The temple was built in the second century BD, and the estate was originally surrounded by a wall that was reconstructed to include a lake and a park with trees and shrubs. The temple or palace was built with rectangular limestone blocks, the largest of which measures seven by three meters. It represents a palace-temple of the estate belonging to the Tobiads who were breeding sacred doves in columbaria. These birds were associated with the cult of Aphrodite which represented a common religion during the Hellenistic period. The columbarium carved into the cliffs of Wadi es Sir resembles columbaria as in Maresha west of Hebron in ancient Idumea which was constructed at about the same time. When Iraq al-Amir was built the population of the area was doing well and was well provided with water. The earthquake in 362 AD destroyed what was left of the palace at that time.

The area of Canaan was disputed by the two Hellenistic rivals for 125 years after Alexander until Antiochus III of the Seleucids incorporated also Judea into his empire and had an altar to Zeus erected in the Temple at Jerusalem. This evoked a revolt by which the Hasmonean kingdom was founded after the army of Antiochus was defeated 164 BD. It has been reported that the Jewish population of the area was assembled in Jerusalem and Judea. While this Hellenistic period on the western side of the Jordan was connected to revolts and wars, on its eastern side, several towns acquired some wealth and started to grow, later to be included in the cities of the Decapolis. Positive change in agriculture is documented for example by *Juglans* pollen in lake deposits indicating introduction of the walnut to orchards.

The Judean king Alexander Jannaeus with an army of mercenaries crossed the Jordan River in 83/82 BD. The destruction of the city of Pella is documented in thick layers of ashy deposits dating to this period. The Seleucid Empire was unable to help Hellenistic cities near Judea since their leaders had troubles among themselves and with the Roman Empire that was becoming more influential in all regions around the Mediterranean Sea. The cities in Jordan recovered from these attacks after the Roman Pompeius liberated them from the Hasmonaean Israel and included Pella, Gadara and Philadelphia among others in the cities of the Decapolis.

Petra region has been settled since the Stone Age with villages as Beidha at the northern margin and later by Edomites which had a fortified town on the highlands above Wadi Musa. The Nabataeans appeared in the 6th century BD as has been noted in Assyrian records since an Assyrian army defeated the Nabataeans, who already dwelt around the Dead Sea at around 647 BD. They resisted the attacks of the Greeks under the Seleucid Antigonos 312 BD. They adapted Hellenistic culture amalgamated it with what they knew from the cultures of Mesopotamia. Thus Petra was founded by a people that may have come from southern Arabia, spoke Arabic and lived from trading goods from southern Arabia and Asia in exchange for such of the Mediterranean region. Their settlement was fed by the water of Ain Musa which issues from the Cretaceous limestone at the entrance to the town, Wadi Musa and they also collected the water of smaller springs of the area. The water was diverted to the city through a system consisting of an interconnected network of ceramic pipes. Along the left hand side of the Siq, representing the narrow canyon, that is the entrance to the city, a covered water channel led water from the springs into the center of Petra. The clay pipes used in addition have tapered ends, something that had been reinvented by modern people much later again. Over the last kilometer the road in the Siq drops strongly and the Nabataean engineers kept the water pipes dropping more slowly so water pressure was high within the city center. The piping networks also included sequential particle settling basins to purify water supplies. Estimates of the total city water input from multiple piping networks and cisterns for collecting rain water uncovered by the excavations indicate that the water supply rate was more than adequate to provide for the needs of the city. The capability of Nabataen water engineers to design a hydraulic system proves their high skill and their water network functioned for a long time.

Throughout the city of Petra hundreds of underground water cisterns are present with walls plastered by cement composed of water-resistant material of high quality. The people of Petra collected so much water that they could afford at the heart of the city center a large open-air pool with a central island-pavilion overlooking a garden terrace. The hills surrounding the city center are filled with rock-hewn cisterns whose contents could be channeled to the site as needed. The northern wall of the pool continued as aqueduct conducting water to a tank which fed into an irrigation system for the gardens on a nearby terrace which below it had a large, underground cistern. Outside the cities, dams closed off wadis to collect water during the rainy season, while stone circles or terraces retarded runoff from slopes and trapped valuable topsoil so that their irrigation lines could feed crops. All along Nabataean caravan routes, secret water collection systems were constructed. A complex system of water collecting was constructed by the Nabataeans on the way to Aqaba in the upper reaches of Wadi Yutum catchment at Humayma with aqueducts and large reservoirs. This collecting system functioned for 600 years still serving Roman and Byzantine to early Islamic inhabitants also as resting station on the way to Aqaba and to Arabian towns in the south. Nabataean influence in the region at the time of Aretas III was to Damascus and they printed coins around 85-60 BD which can still be found in other places in Jordan, such as Pella.

The last Nabataean monarch, Rabbel II, struck a deal with the Romans that as long as they did not attack during his lifetime, they would be allowed to move in after his death in 106 AD. The Nabataeans profited for a while from their incorporation into the trade routes of the Roman Near East, and Petra may have grown to house 20000-30000 people during its best times. However, commerce became less profitable to the Nabataeans with the shift of trade routes to Palmyra in Syria and the expansion of seaborne trade around the Arabian Peninsula. It is not known why the Nabataeans left their capital at Petra, but it seems that the withdrawal was an unhurried and organized process since very few silver coins or valuable possessions have been unearthed at Petra. But it is also possibly their leaving was connected to pollution or even poisoning of their water supply system. When Petra began to be left by its population the Romans had military stations on the highland nearby and also next to the springs supplying drinking water to the city. Abandonment of the city connected to decrease in maintenance of cultivated trees such as olives has been documented by the analysis of deposits by the rock hyrax (*Procavia capensis*). From deposits of their middens (homes) evidence has been assembled that points to a degradation of the Mediterranean forests at the end of imperial city life of Petra, possibly due to the change from the care of orchards and complex irrigation of fields to intensified browsing by livestock. The left-over of digestion of this small mammal that inhabits rocky terrain in Jordan allows the determination of the food they wereable to collect, including parts of plants and snails. The shells of land snails often mark the place of the hyrax home, found among rocky terrains in many parts of Jordan, but similar collections of the shells of land-snails may also be assembled around the home of some rodents living in the area.

Even though, most merchants left the city when trade shifted to Palmyra at Byzantine period, the area of Petra was still inhabited by people who constructed a large church. When it burnt down the fire carbonized some documents of a rich families that lived from the land producing wine, wheat and fruits at around 560 BD and owned property even next to the Mediterranean Sea near Gaza. Only later, the former rich city of Petra disappeared from record.

King Herodes the Great who lived from 67 to 4 BD had more or less friendly relations with the Nabataeans and frequented the healing springs at Ma'in (Zara hot springs) and built a villa in nearby Mukawer (Machaerus). This later fortified place was conquered and destroyed by the Romans when they defeated the revolting Jews in 72 AD. According to tradition, it was at that villa that Salome danced and John the Baptist was beheaded. Zara thermal springs Callirrhoe at the shore of the Dead Sea together with Zarqa Ma’in thermal springs (up to 63°C) about 4km to the NE, form the main hot water springs in Jordan. The basalt nearby is 1.8 Million years old and thus difficult to interpret as source for the heat which therefore may be derived from deep warm layers through which water rises along the fault system of the Jordan Rift. Other thermal springs are present along these faults such as Himma at the Yarmouk in the North and Afra in the valley system of Wadi Hasa further south of Zerqa Ma’in. Between 2100 and 1800 years ago, at the time of the Roman Empire the shore of the Dead Sea was at around 395 m below sea level as is documented from historic anchoring points on the former shores, also from those near Zara hot springs (the sea port of Herodos).

Umm Qais, the Roman city Gadara had a most amazing water supply. This city was founded by the Hellenistic conquerors of Jordan and can be regarded as the replacement of the former village nearby contained within Tel Zira’a. The city Gadara that lies 550 m above Lake Tiberias (ca. 350 m above sea level) collected water in cisterns and used local springs during the first century of its existence. With inclusion into the Roman Empire population as well as economic importance increased since the city was less influenced by the Nabataean and Judean states in the south and west.

The subterranean Qanat Turab was constructed to connect with the spring at the 12 km distant Ain Turab. It was 22 km long since it had to surround valleys. When Hadrian was Roman emperor and with Judea destroyed and Petra included in the Roman Empire economic growth of the cities of the Decapolis in Jordan increased and the people of the city Gadara constructed baths and fountains. Thus even more water was needed and the so called Qanat Fir'aun was constructed. It consists of a 70 km long aqueduct, of which 106 km were below ground in tunnels. One of the subterranean tunnels in the upper Wadi Shallala connects with the Decapolis town Abila that lies 15 km to the north of Irbid near the village Hartha with the city of Gadara. Water has been flowing in that older tunnel of the aqueduct for a long time and has left thick calcareous crusts. With the aid of the Qanat Fira'un about 100 l/s of water were transported into the city Gadara, which increased the amount of water ten times of that available before its construction. Gadara represented an important city of the region which even minted coins since the time of the Roman Emperor Augustus, until 250 year later, the city lost importance when Roman Emperors were changing every few years and usually came from military leaders.

Gerasa (Jerash) another member of the Decapolis represents a relatively large Roman city with very well planed streets, theaters, baths and temples. Here manufactures were excavated which produced large water pots and made leather. Such goods would be needed to supply the army which had to defend the Roman Empire against the east, especially, Persians and marauding Bedouins. Here a large water pond is still found today that served to collect water. Also relicts of an aqueduct are present, which supplied the city with drinking water which was sufficient to keep the numerous fountains of the town running. The decline of the city is documented by the occupation of the hippodrome by squatters and junk yards and its partial use as grave yard. Also the well constructed Roman temples were occupied and exploited for building materials by less well constructed churches during the 7th century AD. The citizens of Gerasa used for their health a mineral spring now called Himmat Jarash which issues at an elevation of 220 m from the gravel of Zerqa River west of Jerash bridge on the road from Amman to Jerash. Temperature of its water ranges from 27 to 29 °C and salinity and alkalinity changes with the season. The water is good for drinking and for taking a bath in it, as was still been utilized by locals until some 30 years ago. While the Romans founded the spring and utilized its water to increase their health, it has only recently been destroyed by modern ignorant people filling the ancient construction of the well with junk.

The Roman city of Pella supplanted the Hellenistic city and of it some spectacular ruins remain. During this period Pella was also one of the cities making up the Decapolis. At the head of the water spring, a small covered theatre and the remains of a bath house are found. These only survived because they were incorporated into the building of the large Byzantine Basilica. The city proper was destroyed by the Golan earthquake of 749. During the Christian empire of Byzantium Pella continued its role as one of the ten administrative cities of Jordan and southern Syria and became the seat of a Bishop and probably was the site of one of the earliest churches. The importance of Pella during the Byzantine period encouraged a building boom and the city was adorned with three churches, the largest one at the head of the spring from which no more water issues at present because it is being pumped off. On the hill above the town a fortress was constructed. It appears that Pella reached its greatest extent during the Byzantine period with well built homes and public buildings. In the surroundings, well organized farms provided the city with food, and from the large number of excavated presses, with ample wine. The production of olive oil and the cultivation of grapes for producing wine can be documented by pollen sequences including deposits of Hellenistic to Byzantine periods, extracted from sections of the Dead Sea sediments.

The Byzantine period can be dated from the year 324 AD, when Emperor Constantine the Great placed the capitol of the Eastern Roman Empire in Byzantium (Istanbul), later named Constantinople. He tolerated Christianity while in Jordan a Christian community developed much earlier, because Pella was a center of refuge for Christians fleeing the upheavals in Judea and the persecution by the Romans during the first century AD. During the Byzantine period all of the major cities of the Roman era continued to flourish, and the regional population boomed. The level of the Dead Sea in the Early Byzantine period rose by up to 10 m compared with that during earlier Roman time. It has been reconstructed that there was more rain in the catchment area of the River Jordan and it was greener in Jordan in general. As Christianity gradually became the accepted religion of the area in the fourth century, churches and chapels were built across Jordan, as can still be seen in Gerasa (Jerash), Philadelphia (Amman), Pella and Madaba where the floor mosaics have been preserved. The one of Madaba is especially interesting because it illustrates a map of the area. Up to the end of this period the cultural roots of the Roman city remained dominant up to the 6th century. A major earthquake struck the country at about 389 AD. Another one left its traces in the sediments of the Dead Sea at 363 AD. The earth quakes damaged the water systems as well as the city walls of Scythopolis which were then renovated. The population of this city during the Roman empire of the 2nd century was estimated to have been about 20000 inhabitants and by the 6th century accordingly doubled. But a plague at 542 AD wiped out much of the population, as it did all over the Byzantine Empire. This bubonic plague killed up to 50% of the population of the Empire. Its Emperor Justinian the Great tried to win back the empire from many kinds of intruders. It was recognized that the level of the Dead Sea from Hellenistic times to Byzantine times wasrelatively high and dropped in Late Byzantine and Umayyad times, but the influence of the climatic change on which this sea level difference is based may be less important regarding life of people in Jordan than the break-down of the Roman Empire and the coming of the medieval Islamic rules.

The distinction between Roman Empire and Byzantine Empire is not well defined but related to the administrative division into western and eastern halves in 285 by Emperor Diocletian, and again the decision of Emperor Constantine the Great in 324 AD to transfer the capital to Byzantium. In Jordan it appears that the foundation of an

Eastern Empire restricted the independence of the cities of the Decapolis as indicated by their no longer minting their own coins but receiving them from the provincial administration center at Antiochia. While the western part of the Roman Empire in the fifth century disintegrated, especially after the sack of Rome by the Germanic invaders in 410 AD, the eastern part continued to exist, but obviously became poorer and also had pestilences spreading such as the plague of Galen. The number of people in Jordan still appears to have remained high, but deterioration of building structure including the water supply indicates a change of life from the producing trades of the city to a more agricultural orientation.

The downfall of the Western Roman Empire with the 5th century not only resulted in a smaller Empire, but that it was now also more affected by the continuous struggle of the Roman–Persian wars which are part of a series of conflicts between states of the Greco-Roman world and the two successive Persian empires of Parthians and Sassanids. Warfare between the Romans and the Persians lasted for seven centuries and the region of the frontier remained largely stable. Towns, fortifications, and whole provinces were repeatedly sacked, captured, destroyed, and traded. Jordan was not directly affected in most of these skirmishes. But one of the reasons for a decrease in the number of inhabitants of Jordan may have its base in the Sassanian invasion of 614 AD that lasted fifteen years, but the Byzantine Emperor Heraclius managed to recover the area in 629 AD. The Byzantines and the Sassanids as well sponsored nomadic mercenaries from the desert stemming from central or southern Arabia. Justinian viewed his mercenaries the Ghassinids as so valued for preventing conflict that he awarded their chief with titles including king. The Sassanians allied with the Lakhmids which were also Christian Arabs, but from the area of modern day Iraq. Many Jordanian families trace their roots to Ghassanid ancestors, which had obviously settled especially around Amman and in the South of Jordan, especially Karak.

Pollen found in sediments which were deposited during the late time of the Byzantine Empire and of the first Islamic states indicate a return of forest, first with dominance of the fast growing pines, later that of *Quercus* (oaks), *Pistacia* and *Sarcopterium*, the last representing a prickly shrub that grows commonly on degraded agricultural land. Also the influence of the olive tree decreased, documenting the abandonment of most gardens which were settled by pines instead. Between the fifth and eighth century the level of the Dead Sea sank, which indicates a drier climate. In Jordan the change of vegetation types was clearly due to the decline of agriculture, tending of fields, the increase of nomadic life and dependence on goats and sheep. This change was probably connected to a sharp decline in population, not only here, but also in many places around the Mediterranean and the areas formerly occupied by the Roman Empire. Cities lost influence when they lost contact to the Byzantine Empire and people moved to small villages and lived from the land. The change to lesser population in Jordan continued into early Islamic period, especially affecting the cities.

Emerging from southeastern Arabia, the Muslims invaded Syria, defeating the Byzantines and also quickly conquering the collapsing Persian Empire. In the year 636 AD, the Muslim armies overran the Jordanian highlands, conquered the Jordan Valley in the Battle of Fahl near Pella and won a decisive battle against the Byzantines on the banks of the Yarmouk River. This victory opened the way to the conquest of Syria, and the remaining Byzantine troops were forced to retreat into Anatolia only a few years later. Jordan is said to have prospered during the following Umayyad period (661-750 AD) due to its proximity to the capital city of Damascus. In 747 or 749 AD, a severe earthquake destroyed Pella - toppling the churches and crushing the houses of the Umayyad complex- it also struck Philadelphia (Amman), Gadara and Gerasa. Its destruction may have contributed to the defeat of the Umayyads by the Abbasids a few years later. The earth quake leveled Scythopolis on the western side of the Jordan and it hit also other places especially around Lake Tiberias. Ample evidence of the destructive power of this earthquake was uncovered at Pella where even skeletons of cats, which were too slow to escape the collapsing buildings, were excavated. After this disaster, the main center of Pella moved to an area to the north of the main mound. For the next one thousand two hundred years, Pella continued to exist as a small town. Abbasid pottery, a Mamluk Mosque and Ottoman sugar mills document continuity and the life of a minor town.

By 750 the power of ruling the country moved to the Abbasids with their capital in Baghdad and Jordan thus lay far from the center of the empire. The Desert Castles that were built by the Umayyad rulers were abandoned, and Jordan was generally neglected. It has been suggested that the population of Jordan increased again until about the beginning of the 9th century AD. The invasion of the Crusaders began in 1096 AD and resulted in the conquest of Jerusalem by Christian forces predominantly from France and Germany and the establishment of a kingdom there. To protect the route to Jerusalem a line of fortresses was built along the backbone of Jordan with the most substantial of these at Karak and Shobak. After having unified Syria and Egypt under his control Saladin defeated the Crusaders 1187 AD and Karak castle changed its ownership only 46 years after it was built. Shobak castle was built in 1115 AD by King Baldwin during his expedition to the area, when the captured Aqaba in 1116. It was strategically located along the pilgrimage and caravan routes from Syria to Arabia. This allowed the control of commerce of the area, as pilgrims and merchants needed permission to travel past it. It was surrounded by relatively fertile land, and two cisterns were carved into the hill, with a long, steep staircase leading to springs within the hill itself.

In the year 1258 AD, an invasion of Mongols reached Jordan. They were eventually turned back two years later by the Mamluk Sultan Baybars who had his capital in Cairo. The unification of Syria, Egypt and Jordan led to some prosperity for Jordan. Sugar was widely produced and refined at water-driven mills along the rivers and creeks ending in the Jordan Valley. This may go along with a period of more rain during the Mamluk period 9th the 12th the 14th century, as was reconstructed from data extracted from pollen analysis. Many of these water courses are nowadays dry.

Another Mongol invasion in 1401 AD, combined with weak government and widespread disease, weakened the entire region.

For more than 250 years thereafter, Syria including Jordan was ruled by Mamluk sultans from 1260 to 1516. During that time the most important place was Jerusalem which was a marginal city but of high religious importance. Clerics governed and concentrate on building the Islamic religious buildings in the city. Administration of the country was neglected, and the population was largely poor. Four centuries of Ottoman rule (1516-1918 AD) followed and was a period of general stagnation in Jordan. The Ottomans were primarily interested in Jordan in terms of its importance to the pilgrimage route to Mecca, and along this, a series of square fortresses to protect pilgrims from the desert tribes and to provide them with sources of food and water. The Ottoman administration was weak and could not effectively control the nomadic Arab tribes. Over the course of Ottoman rule, many towns and villages were abandoned, agriculture declined, and families and tribes moved frequently from one village to another. Water collecting systems were abandoned often even filled with waste. A period with more rain in the Late Ottoman time did not increase the use of the land, but rather increased the danger of Malaria due to the formation of wet places used as breeding sites of mosquitoes.

The previous brief historic recapitulation was written to illustrate that the history of the country was mainly determined by one major and single factor, which is the availability of continuous water sources. Conquering any of the historic kingdoms or city states was easiest by controlling its water supply system. Spring water was diverted to supply Ain Ghazal, Petra, Pella, Philadelphia, Gadara and many other towns, city states and kingdoms. Several of the highland city states and kingdoms, such as Hisbon (Hisban), Medaba (Madaba), Dhibon (Thieban) and others depended historically on house and community cisterns and water collection pools.

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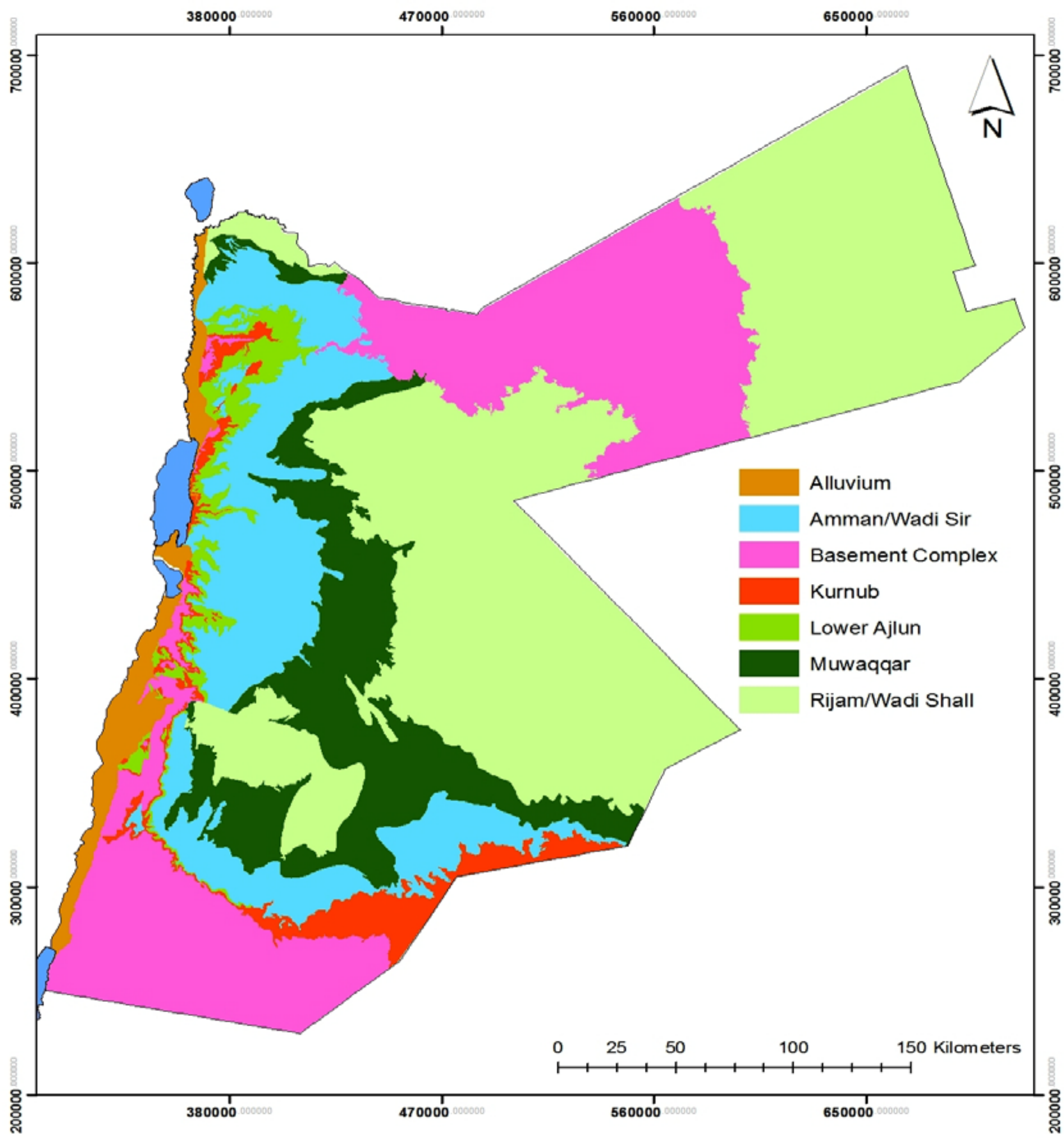
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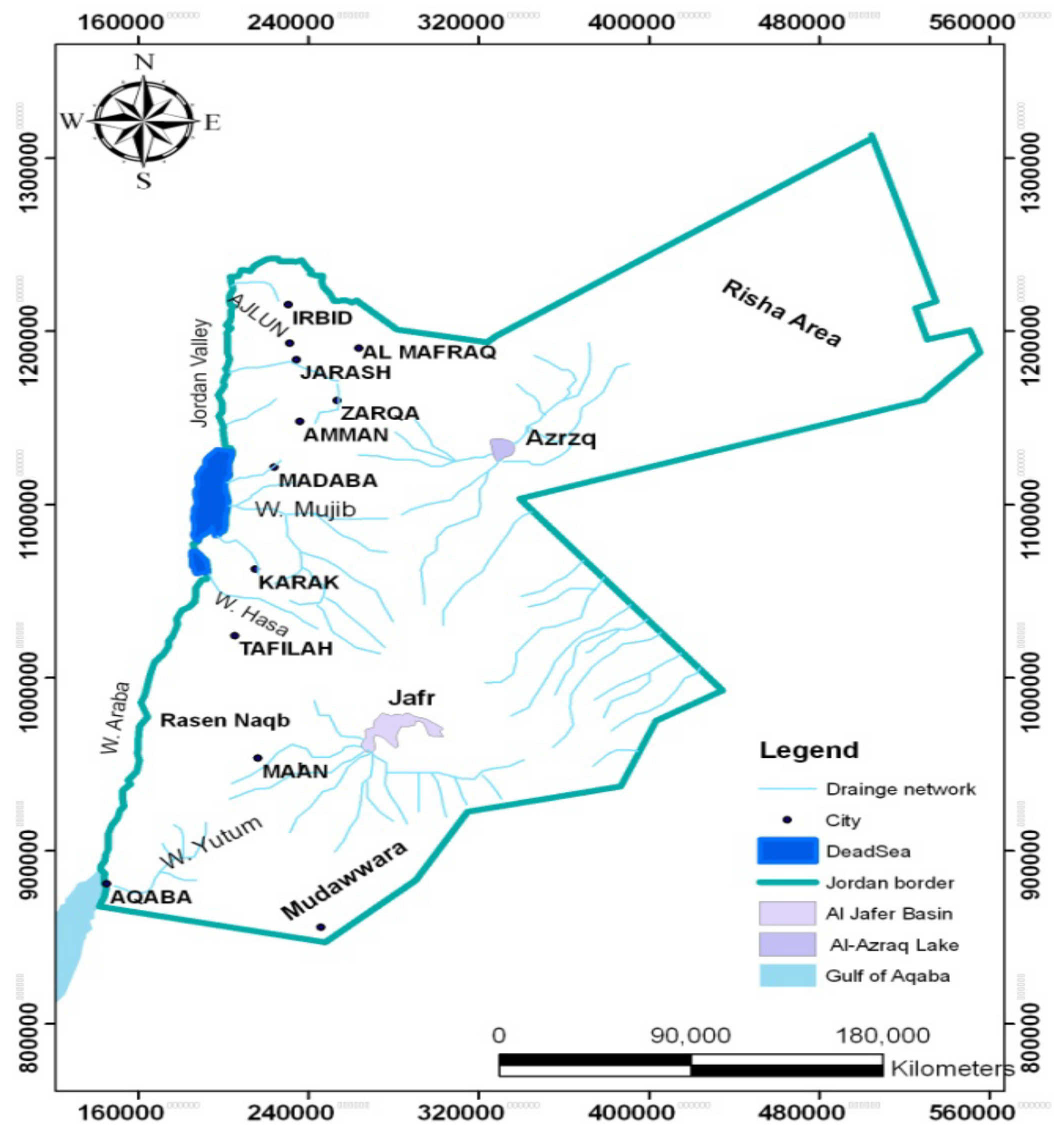

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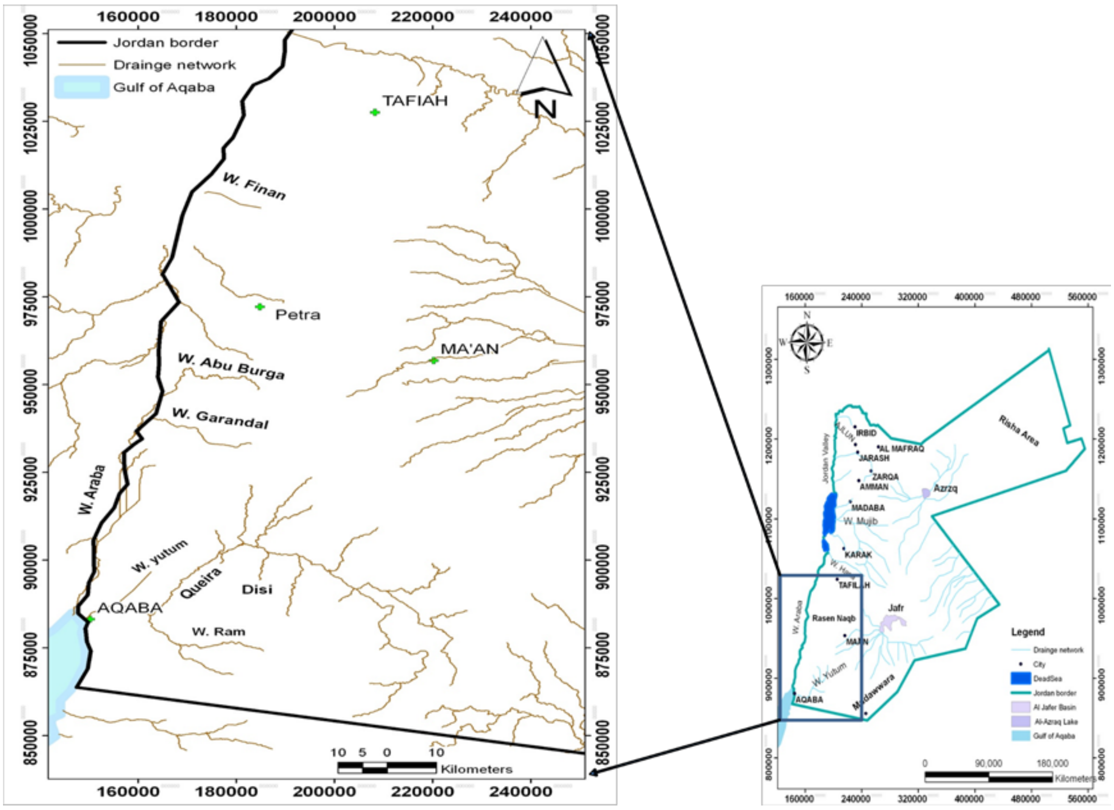
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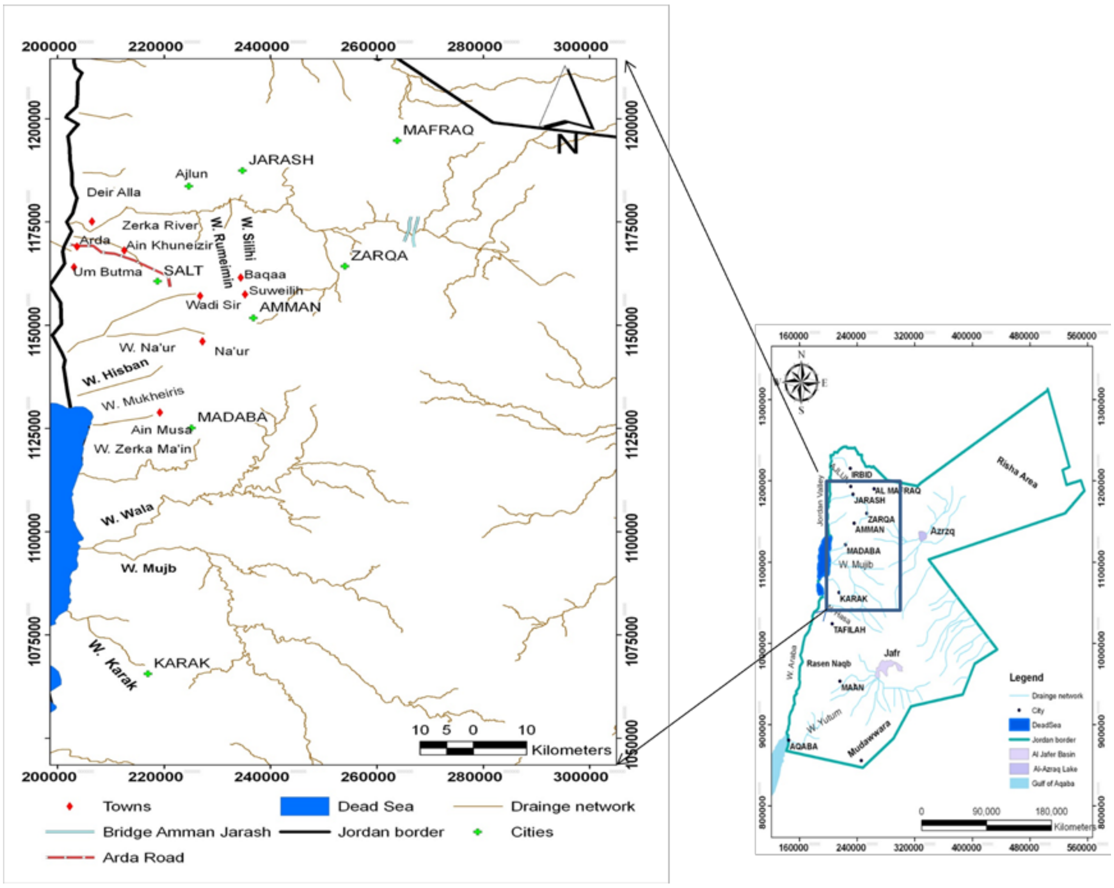
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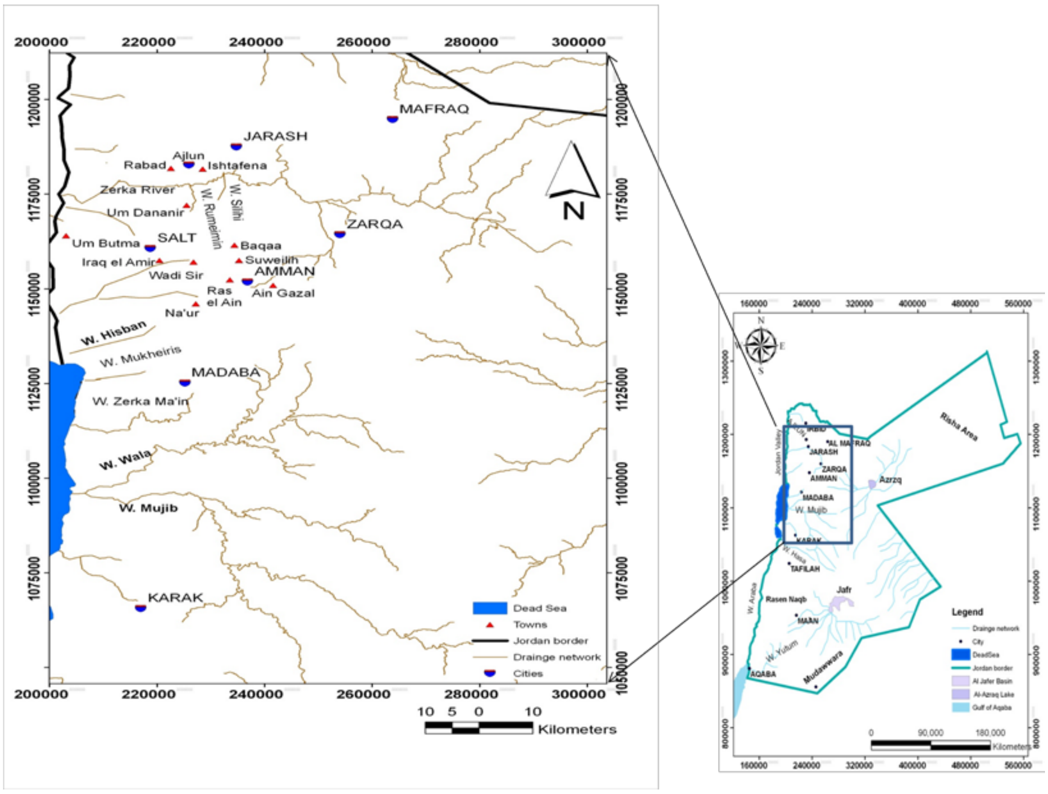
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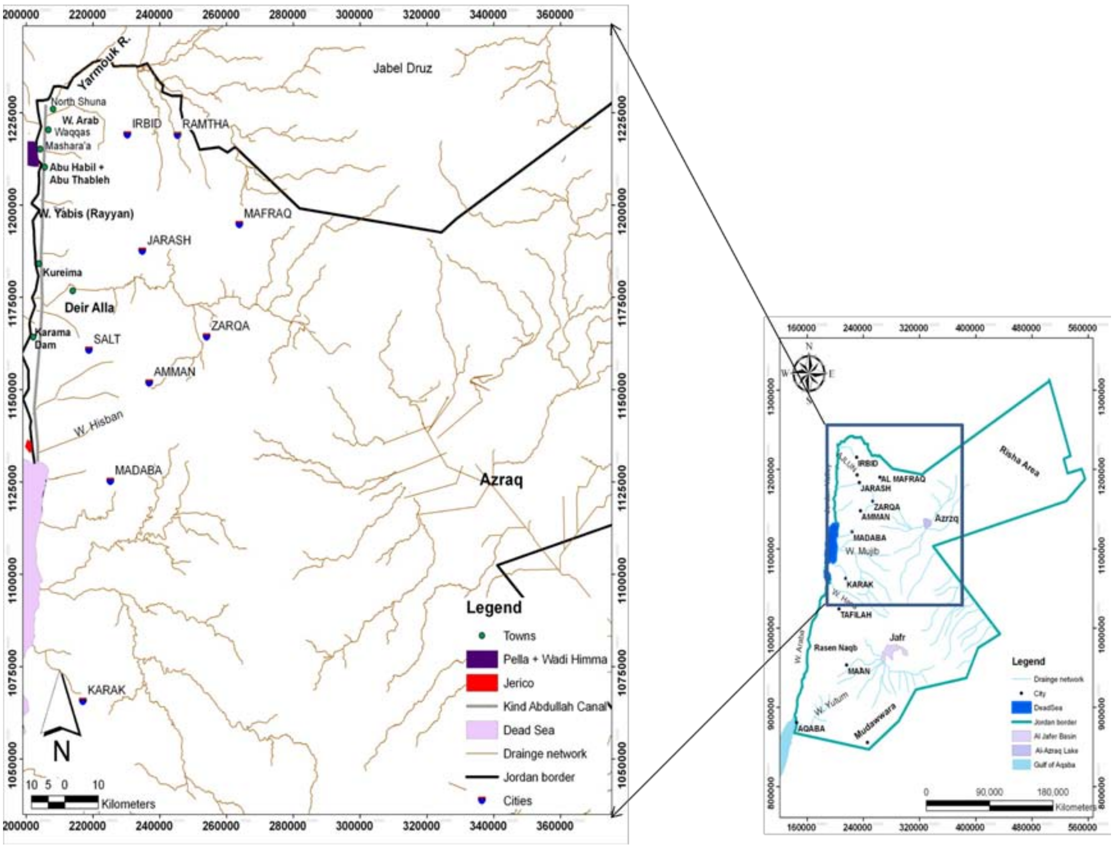
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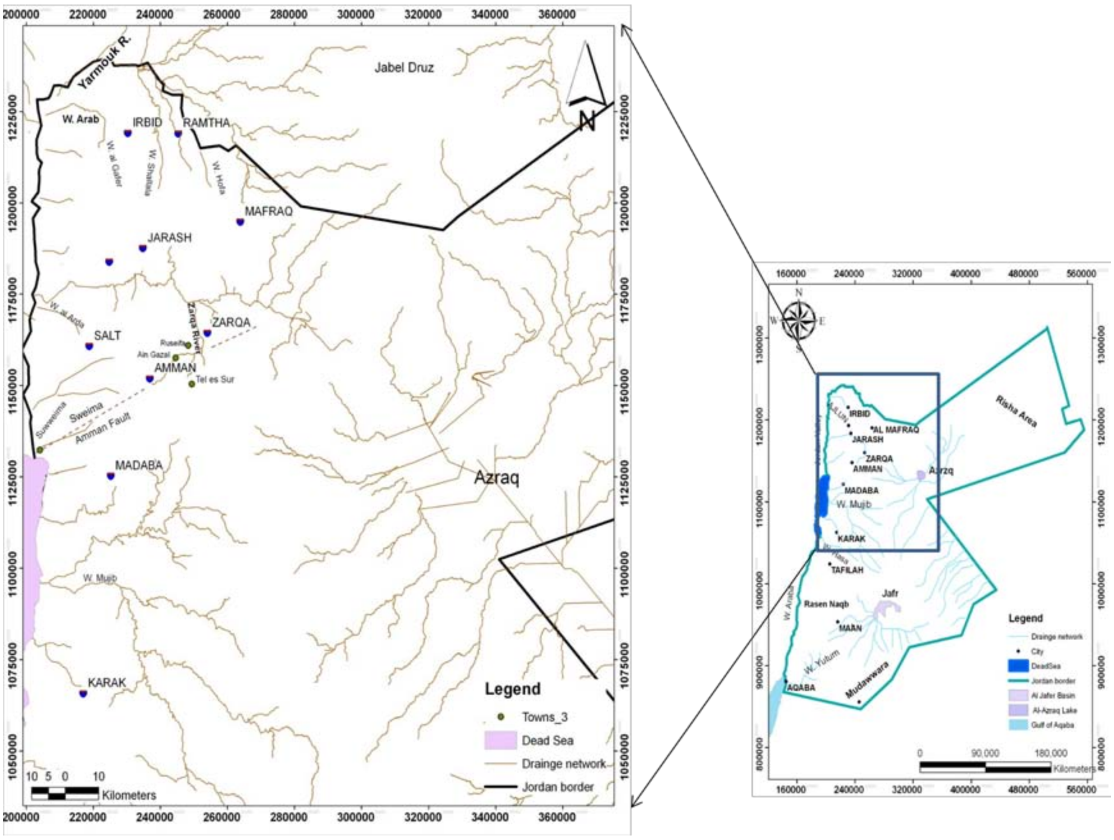
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Waqf as Suwwan impact crater, East of Jordan