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Geologic evolution of the Tertiary-Quaternary Jordan Valley with introduction of the Bakura Formation

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with 45 figures

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Abstract

The reconstruction of the geological history of the Jordan Valley is based on interpreting its sediments and fossils reflecting the presense of sea bay at Late Oligocene up to the formation of the present salty Dead Sea during the Holocene. The Late Tethys – Early Mediterranean Sea had entered the northern Rift valley during the early stage of its formation. The Tayba Formation reflects the presence of a shallow sea within the Rift as exposed at Wadi Al Qarn near the town Abu Habil and beaches of that sea with coastal fauna along the eastern side of the rift-valley near to the towns Shuna and Waqqas. First saline deposits evolved when the sea withdrew during early Miocene as exposed near Waqqas. Rivers coming from the East discarted their gravel consisting of eroded limestones and

flint of Late Cretaceous to Eocene deposits into the new depression. Channels filled with alluvial gravel are exposed to the east of the eastern Rift margin and west of the town Awsara.
During the latest Miocene, in the Messinian period, the Mediterranean Basin to the West had lost most of its water due to closure of the connection to the Atlantic Ocean and strong evaporation. The continental slope at the western Levant became dry land while the up to 3 km deep depression of the Levantine Basin developed to the west of it. It is assumed that a river coming from the Arabian Sirhan Depression in the east and crossed the Rift. It excavated a valley, the Beisan Canyon, which connected the Rift Valley with the Qishon Canyon on the continental slope in the West. That river ended near the large salt lake on the base of the Levantine low in the Mediterranen Basin. During a late stage of the Messinian fresh water, coming from the Paratethys in the east, brought a fauna of the Lago Mare Period and it reached the Levantine Basin. It entered the Jordan Valley depression following the river through Beisan Canyon. With it the characteristic molluscan fauna of fresh water entered the Rift and has since developed into the characteristic fresh water fauna of Jordan.
During the following Zanklean flood that filled the Mediterranean Basin with sea water coming from the Atlantic Ocean, the salty water of the Levantine salt lake was pushed into the Rift Valley using Qishon Canyon in the slope and Wadi Beisan. In the deeper parts of the Rift lakes of salt enriched sea water developed into the Sedom lagoons. Here the brines mixed with carbonate rich water from rivers and ground water predominantly coming from the eastern land.
The connection of the salt lakes in the Jordan-Dead Sea Rift with the Mediterranean Sea was subsequently closed by alluvial deposits originated predominantely from erosion in the east and by volcanic material. Soil and gravel covered the salt flats that had formed in the northern part of the Jordan Rift and sealed them. Larger and smaller lakes along with creeks and rivers provided the environment in which the mollusks of the type as are characteristic to the Lago Mare Fauna could live and evolve. The most conspicuous species belong to *Melanopsis*, *Melanoides* and *Theodoxus* and they among several other fresh water and land molluscs characterize the fauna of the Al Qarn Formation exposed on the margin of King Abdulla Canal just SW of Al Qarn ridge and west of the town Abu Habil. The lake deposits are underain and covered by alluvial gravel and these cover deformed Tayba Formation. The beds of Al Qarn Formation were also deformed and inclined to the west, similar to the alluvial deposits of Ghor al Katar exposed in the top of a saltdome at the reservoir of Karama Lake. The Wadi Al Qarn Sill developed forming a structure crossing the Jordan Rift that may correspond to the Marma Feiyad Sill reported from the western side of the Rift.
North of Al Qarn sill a flat valley floor evolved in the Rift depression in which a spring fed lake deposited Aramshi Formation. Its limestones overlie a truncated basalt pipe that may be time equivalent to the basalt dyke that overlies the alluvial Ghor al Katar Formation. Aramshi Formation is a relict of a former higher Jordan Valley Rift flat preserved north of Waqqas as flat topped hill. It became slightly tilted and its hard limestones were excavated when the alluvial flat of the Ghor formed, into which subsequently Bakura River excavated its valley. The molluscs living in or near Bakura River are very similar to those that lived in the Jordan River in historic times. Bakura River issued into Lake Samra that was larger than the modern Dead Sea but smaller than Lake Lisan. Rivers coming from the east discharged their gravel directly into Bakura River. As Samra Lake expanded it changed into the less salty Lake Lisan, which had its largest extension when it covered the whole Jordanian portion of the former Bakura River bed and had its shore just south of Lake Tiberias. The Wadi al Qarn Sill periodically divided Lake Lisan into a northern less salty and a southern more salty part. Plankton blooms of diatoms formed thin bedded diatomites north of the sill. After Lake Lisan had withdrawn most alluvials no longer reached the river but were deposited on the margin of the Ghor before they reach the Zor of River Jordan. The small rivers and creeks coming from the east discharged their water by way of the same valleys that had been excavated during and before deposition of Bakura Formation. As Lake Lisan was reduced in size due to evaporation and when its southern lake shore lay near Karama reservoir dam, the salinity of the lake had risen and deposits formed by it were dominated by gypsum.
The thick salt deposits present in the subsurface of the basins around Lake Tiberias, in the Karama area and in the Dead Sea Basin were mobilzed by structural unrest and formed diapirs. During existence of Lake Lisan a salt dome near Karama reservoir dam pushed the Ghor al Katar gravel Formation up to form an island with beach around it. Above that alluvial deposits and soils of Damya Formation were locally deposited before Lake Lisan had been transformed into the Dead Sea.

Zusammenfassung

Die geologische Geschichte des Jordangrabens wird rekonstruiert vornehmlich basierend auf Befunden, die in seinem östlichen (jordanischen) Anteil aufgeschlossen sind. Schon bei Beginn seiner Entstehung erreichte ein Ausläufer des sich aus der Tethys entwickelnden Mittelmeers den einsinkenden Rift-Graben und hinterließ dort Ablagerungen der Tayba Formation. Diese sind als Beckensedimente westlich des Ortes Abu Habil im Wadi al Qarn aufgeschlossen und zum anderen als Strand-nahe Bildungen am Rand des Grabenbruches bei den Orten Nord Shuna und Waqqas. Als das Meer sich im älteren Miozän zurückzog, entstanden auch kurzzeitig Salinar-

Ablagerungen. Vom arabischen Festland wurden zudem Abtragungsprodukte und dabei besonders Flussgerölle eingeschüttet, deren Zusammensetzung belegt, dass die Meeresablagerungen des Alttertiärs und der oberen Kreide lokal bereits abgetragen wurden, während andere östliche und nördliche Teile der Region noch von Meer bedeckt waren. Während des späteren Miozäns war die Region Land und der Jordan-Graben sank weiter ein. Während der Messinischen Phase trocknete das Mittelmeer aus und unterhalb des levantinischen Kontinentalrandes entstand ein Salzsee, dessen Oberfläche tief unter dem Niveau des Jordangrabens lag. Mit ihm verband sich ein vom arabischen Kontinent kommender Fluss, der die Schlucht des Beisan Canyons austiefte und über den Qishon Canyon ins östliche levantinische Mittelmeerbecken mündete. Die mächtigen Ablagerungen dieses Salzsees, der bis zu 3000 m unter dem Meeresniveau lag, wurden von Sanden des Nils teils überdeckt. Während der Lago Mare Phase kam Süßwasser aus den Seen und Flüssen der Paratethys und erreichten auch den Beisan-Fluss. Die charakteristische Fauna wanderte in das Jordan-Rift und weiter nach Osten ein und ist noch heute für die jordanischen Süßwasser- Fauna bestimmend.
Als das Meer in das Becken des Mittelmeeres zurückkehrte, presste es Salzwasser aus dem levantinischen Salzsee durch den Beisan Canyon in die Jordan-Senke. Hier entstanden mehrere Salzseen, in denen die Salze der Sedom Formation ablagert wurden. Diese sind im Untergrund des nördlichen Jordan-Grabens erbohrt und im Toten Meer als mächtige Salzlager sowie gelöst im Salzsee vorhanden. Die nördlichen Salze wurden von Flussablagerungen überdeckt. Darüber konnte sich die Lago Mare Fauna in Teichen, Sümpfen und Seen während des Pliozän–Pleistozäns weiter entwickeln. Hiervon zeugt die Al Qarn Formation mit reicher Fauna, die bei Abu Habil aufgeschlossen ist. Die Fluss- und Seeablagerungen dieser Formation überlagern bereits verkippte Sedimente der Tayba Formation mit deutlicher Winkeldiskordanz und wurden ihrerseits nach ihrer Ablagerung verkippt. Gleichzeitig wurden die Flussschotter der Ghor al Katar Formation weiter südlich im Rift abgelagert und anschließend auch schräg gestellt.
Im Jordan-Graben bildete sich in der Folge eine Tal-Ebene aus, von der nur geringe Reste mit der Aramshi Formation erhalten sind. Diese entstand nach einer Phase von geringem Vulkanismus im Tal in einem Tal-See mit Quelle kalkhaltigen Wassers. Die Ablagerung mit reicher Mollusken-Fauna wurde als kalkiger Härtling später schwach gekippt und von der Erosion freigelegt noch ehe sich der Bakura Fluss in die Ebene eingraben konnte. Vorher oder gleichzeitig begannen der starke Anstieg des arabischen Hochlandes und die Ausräumung der Seitentäler.
Der Bakura Fluss, der im Wesentlichen im Bett des heutigen Jordan-Flusses verlief, mündete in den salzigen Samra See, der etwas größer war, als es das heutige Tote Meer ist. Die Seitenflüsse schütteten ihre Fracht direkt in den Bakura Fluss, während diese heute den Jordan Fluss meist nicht mehr erreicht. Wasserreiche Zuflüsse wandelten den Samra See in den Lisan See um. Durch den kräftigen Anstieg wurde das Jordantal bis an den Südrand des Sees Genezaret überflutet. Der Lisan See war nicht so salzig wie das Tote Meer und seine reiche Diatomeenflora wurde besonders in seinen nördlichen Teil als Diatomite abgelagert. Bei dem Rückzug des Lisan Sees sorgte eine Schwelle bei Al Qarn dafür, dass im nördlichen Teil des Sees das Wasser weniger salzig war als im südlichen Teil. Beim weiteren Schrumpfen des Sees wurden südlich von Schwellen, die bei Karama von Diapiren gebildet wurden, anfangs Gipse abgelagert, ehe sich der See vor etwa 20000 Jahren ins Tote Meer wandelte. Die Verkleinerung des Sees beruht auch auf einer Abnahme der Menge des vom Osten angelieferten Wassers, ausgelöst durch eine von vulkanischen Produkten gebildeten Schwelle.

1 Introduction

The Jordan Valley extends from Lake Tiberias at an elevation of 212 m below Sea Level southward to the Dead Sea at an elevation of less than -429 m (2016). Its width just to the north of the Dead Sea is around 20 km. In its northern part the width is around 10 km with a minimum in its central part of 4 km. On the eastern side of the Jordan River the width of the Ghor (Ghor = Jordan Valley) that is the flat area above the central valley of the Jordan River varies between 4 and 6 km and only just north of the Dead Sea, the Jordan Disk is wider. The length of the Jordan Valley between Lake Tiberias and the Dead Sea is 105 km. It is bordered on the eastern side by high, steep escarpments with differences in elevations between the valley floor and the surrounding mountains of 1.200 m. On the western side the northern part is formed by the hilly Galilee and the central part by the Judaea mountains which are almost as high as the mountains on the eastern side. Jordan River has excavated a more or less narrow central valley with steep sides to the Ghor, and the basal flood plain of the river is called the Zor.
Here we focus on Neogene to Pleistocene sediments exposed on the eastern side of the Jordan Valley. The Jordan Valley between the Yarmouk River entering the Jordan River near Bakura south of Lake Tiberias and the Dead Sea differs in shape in regard to its northern, middle and southern parts. South of Lake Tiberias it forms a basically plane region that is inclined somewhat to the west. Here the Jordan River excavated its meandering course on its western margin. 35 km to the south near the Al Qarn ridge at the mouth of Wadi el Malih from the west and Wadi al Yabis from the East, the Ghor is narrow and the Zor is deeper and also narrower with fewer and smaller meanders of River Jordan. South of Wadi Rajib the Ghor becomes wider again and also the Zor is wider with steep slopes on both sides, the barren Katar. Downriver at the mouth of Zarqa River in the Karama area the Ghor is hillier with

a salt dome just below the Lisan deposits in the area of Karama Dam. Further south to the Dead Sea, the valley widens forming the Jordan Disk with a width more than 20 km near Jericho. South of Kafrein and Hisban creeks confluences into the Jordan River meanders end and the river has eroded an almost straight canal that has cut deep into its bed caused by the drastic fall of the Dead Sea level during the past 50 years. The localities and formations dealt with in this study include Tayba, Amora-Gomorra, Al Qarn, Aramshi, Bakura, and Lisan Lake Formations.

Fig. 1: The Jordan Valley in position of its greatest width close to the Dead Sea forms the Jordan Disk between the eastern slope of the Valley and the northern end of the Dead Sea. On the eastern side the road from Amman and Wadi Shueib Reservoir and on the western side is Jericho-Oasis are shown. The meanders of Jordan River end near the flat exposed since historic time of Dead Sea regression. (Scale is 6.45 km; from Google Earth 2016)

2 Structural and tectonic setting

The African Plate is one of the plates that formed when Gondwana collided with Eurasia and subsequently broke into several plates. During this process the Tethys Ocean regressed at the Eocene from the Arabian plate, the area now occupied by Jordan became land. In late Eocene the Tethys Ocean shrank in size to form the Mediterranean Sea during the Oligocene and terrestrial erosion began affecting the land of Jordan. Within the Late Oligocene the sea again flooded parts of northern Jordan and also entered the northern part of the forming Jordan Rift. The depression of the new rift began to collect predominantly clastic sediments which were predominantly eroded from the Arabian side of the rift which is now Jordan's highland. Sea water found a way into the depression and when it withdrew deposits of saline environment were covered by the terrestrial debris (ref. see Bandel & Salameh, 2013).

The major structure affecting the Jordan Valley deposits is the strike slip fault, which is continuous in the central part of the valley from the Dead Sea to Deir Alla and runs along the foothills of the eastern mountains from Deir Alla to the mouth of the Yarmouk River. This study concentrates on the Neogene to early Pleistocene sediments on the eastern side of the lower Jordan Valley especially, in its northern part extending from the northern end of the Dead Sea to Zarqa River and to Yarmouk River. The sediments and the fossil in them reflect the depositional environment and the tectonic movements in the Jordan Rift Valley after the main regression during the Eocene.

The strike-slip nature of the Dead Sea fault zone was recognized by Dubertret (1932) and Quennell (1958) and had already been noted by Lartet (1869). Its origin was contemporaneous with that of the Red Sea which began at the same time by spreading, and it was connected with a collision zone in the Taurus Mountains of southeastern Turkey. In the central part of the Jordan Rift lies the Dead Sea basin that is over 130 km long and 7–18 km wide with the Moho at a depth of 32 km (Marco, 2007). The sinistral strike slip movement along the Jordan transform fault of approximately 120 km (Burdon, 1959; Freund, 1970; Freund et al. 1970; Bandel, 1981 and others) continues to the present time with an average slip of 4–6 mm/yr for approximately 25 Million years (5–7 mm according to Ben Avraham et al., 2008). The vertical movement connected to that lateral movement was different in the sections of the rift, with up to 12 km subsidence in the Dead Sea basin (Götze et al., 2007), while crust thickness at the edge to the Mediterranean is much thinner, and it is around 7 km for the Tiberias basin. In case motion along the transform may have been more or less continuous since it had begun, and had started within the Oligocene. It is assumed that Arabia had moved more than 80 km against the Levantine block by the Messinian at about 5 Million years ago. The floor of the Rift continued to sink until it lay well below sea level. The timing of lateral and vertical motion within the Jordan Rift is not known in detail.

Salameh & Farajat (2007) reconstructed the flow of water into the rift as coming predominantly from the eastern side using the Sirhan depression including the Azraq Basin until the Pleistocene. Sediments and water were thus discharged into the Jordan Rift Valley coming predominantly from the east. They suggested a still-stand period between the two main phases of strike-slip movements of 62 and 45 km beginning in the Miocene and again from Pleistocene to present. Due to the large catchment area of Sirhan Depression, at that time, of around 120.000 km^2, SALAMEH & FARAJAT (2007) suggested that Sirhan Depression was the source area for most of the sediments deposited in the Jordan Valley.

3 The end of the period of the shelf sea in Jordan

The base of the Jurassic deposits in Jordan is formed by an erosive surface on Late Triassic sediments composed of deposits of a sort of Keuper of the southern Hemisphere. Here on the Gondwana area south of the Tethys Ocean a phase of deposition in a salty sea ended (BANDEL & KHOURI, 1981). During the early Jurassic the sea reached Jordan again and sea shore changed back and forth in the area with the Tethys Ocean to the North of Jordan (BANDEL, 1981). Jurassic deposits were partly eroded before the Early Cretaceous Kurnub Sandstone was laid down on a flat margin of the southern Gondwana Continent. Before Kurnub rivers deposited their sand the landscape had been fractured into blocks which had been truncated. From them all younger Jurassic sediments were eroded. The Early Cretaceous Kurnub Formation changed its river character from South and Central Jordan to further North and East to more and more influence of marine intercalations (ref. see BANDEL & SHINAQ, 1998). During Mid Cretaceous this area was largely flooded by the Tethys Ocean. The structural unrest during the Campanian did not only take part in phosphate production, but also created a hilly landscape, which was partly exposed above sea level at the KT-boundary, partly remained below water surface (ref. see BANDEL & SALAMEH, 2012). The stable southern margin of Gondwana with relatively smooth morphology all the way to the south of Jordan had been covered by a shallow sea from the begin of the Cenomanian in the Cretaceous to the Late Eocene of the Tertiary (BANDEL & SHINAQ, 1998). It subsequently turned to become land (WETZEL & MORTON, 1958; BENDER, 1968). A varied landscape formed with relatively flat surface but also regions with raised areas in which erosion began and rivers produced gravel. This land surface of the post Eocene time became partly flooded during Late Oligocene by the sea- that may have come from the East or from the Mediterranean Sea which evolved during that time from the Tethys Ocean.

The Jordan-Dead Sea Rift formed in connection to the movements of the African Plate in regard to the Arabian plate (SCHANDELMEIER et al., 1997; FLEXER et al., 2005, and references there). During mid Tertiary time the separation of Arabia along the Jordan Rift began jointly with the lowering of the rift base and a rise of its margins. At latest during Oligocene to Early Miocene a fracture between the Arabian and the Palestinean blocks resulted in the formation of a graben, the Jordan rift valley (see HIRSCH, 2005, for references). Deposits formed during that time are not of great thickness, but they are well represented in the area of the eastern side of Lake Tiberias and along the eastern Rift all the way to Masharia-Pella and Abu Habil and as far east as Azraq (BENDER, 1968; BANDEL, & SHINAQ, 2003 for references).

The amount of motion along the faults of the rift valley of the Levant plate in relation to the Arabian plate is known. It is unknown however how much movement occurred during a specific time in horizontal and vertical direction, when and how much. Also unknown is whether movements in vertical direction were connected to those of lateral ones or occurred independently of them and also the time of upward movement of the rift margins is still to be elucidated in detail.

4 Transgression during late Oligocene

The Tethys Ocean to the West of the Levantine (Palestinean) block slowly evolved into the Mediterranean Sea and MEULENKAMP & SISSINGH (2003) reconstructed that the Arabian Platform was still largely covered by the sea in Early to Middle Eocene times. It was subsequently subject to a major regression in the Middle to Late Eocene and at Early Oligocene, it was almost completely emerged. During the Oligocene the Gulf of Aden - Red Sea-Gulf of Suez Rift System began to form and separated the African and Arabian plates from each other. It is suggested that initial rifting may have started around 30–27 Million years ago. In connection to the onset of rifting and opening of the Gulf of Suez, during the Late Oligocene, left-lateral displacements along the Dead Sea transform fault started. With the end of the Eocene and begin of the Oligocene the sea withdrew and the area was uplifted and eroded. It has been assumed that eroded deposits have been carried to the Mediterranean Sea. But as soon as the newly forming and strongly subsiding rift valley formed the rivers deposited their gravels here (BANDEL & SHINAQ, 2003, and references therein).

It can thus be resumed that about 24 million years ago the area now occupied by the Jordan Valley in northern Jordan between the towns of Abu Habil and North Shuna was inundated by the sea coming from the north, and may have even been connected to the Indo-Pacific Ocean via the Damascus Basin at least intermittently. What is now the steep eastern slope of the Jordan Rift Valley at that time represented the shore, with unknown character in the west of the Rift Valley. All outcrops from the towns of North Shuna to Waqqas are in more or less continuous contact with each other. They represent beach or near the beach deposits, and further in the south at Abu Habil exposed in Wadi al Qarn deposits occurred in shallow water and within and environment of intertidal flats. The shore of the sea within the northern Jordan Rift has left it traces in the slope and base in the Jordan Valley between Shuna near Yarmouk River and Wadi al Qarn near Abu Habil to the south of it. Into the near-shore environment, rivers coming from the east deposited pebbles documenting erosion that uncovered continuously older beds of Paleogene age above to Late Cretaceous age below (BANDEL & SHINAQ, 2003, and references therein).

The northern part of Jordan was last flooded by the remnant of the Tethys Sea which apparently came from the NW when it flooded part of the Arabian plate during the Late Oligocene (RÖGL, 1996, 1998; BANDEL & SHINAQ, 2003). This sea also covered parts of eastern Jordan and its near-shore deposits are preserved near the Oases of Azraq and the Jafr depression (BENDER, 1968; ZACHROS et al., 2008). BENDER (1968) also reported deposits near the basalt occurrence of Jebel el Druz in NE Jordan which contained sharks teeth of the type of *Carcharodon* of Oligocene to Miocene age. This is probably the locality at Wadi al Ghadaf or near to it from where ZACHROS et al. (2008) described sea urchins which they determined as of Oligocene age. WETZEL & MORTON (1959) had noted bivalves of pectinid shape from near the town of North Shuna which COX (1934) described and determined as *Chlamys judaica*. WIESEMANN & ABDULLATIF (1963) measured a section of 40 m of glauconitic sandstone near North Shuna and noted sea urchins determined as *Echinolampas* and *Clypeaster* and the bivalve *Pholadomyas*. BENDER (1968) noted the presense of these "Taiyba Beds" of WETZEL & MORTON (1959) between the mouth of the Wadi el-Arab in North Shuna and Wadi Tayba and determined them to have a questionable Oligocene and safer Miocene age.

The section near the town Waqqas exposes the transition from Paleogene to Neogene as almost concordant, but sharp boundary (BANDEL & SHINAQ, 2003). The angle formed between beds of the Late Cretaceous surface and the Tertiary deposits is inconspicuous, dipping west with 30° towards the Jordan Valley. The sandy beach rock at the base differs in thickness from 4–6 m with glauconitic grains mixed by. On surfaces oyster settled and are still preserved in their place of growth. Also present are crab burrows with their walls enforced by brick-like fecal pellets. The quartz rich coarse sandstone is cemented by a carbonate matrix and contains green glauconite. A nodular limestone above has along with the oysters the molds of large gastropods belonging to turritellids, ficids, naticids and strombids (BANDEL & SHINAQ, 2003: Pl. 3). Small colonial corals have been bored by bivalves that lived within them. The limestone is overlain by sand and gravel containing limestone clasts that had been settled by boring organisms. Above sand and gravel beds follow with variable thickness. The gravel above of approximately 5 m in thickness contains layers of stromatolitic limestone. These deposits formed by bacterial crust document that salinity had risen. Saline deposits compose the top of the section and from them salt and gypsum has subsequently been leached resulting in the formation of a characteristic cellular dolomite. The whole was covered by alluvial gravel.

In Wadi Tayba, the next ravine in the slope to the south of the town of Waqqas, the exposed sequence dips with varying degrees towards west. Here also pectinid and clypeasteroid sea urchins are present, and in limy beds large foraminifera (genus *Lepidocyclina*, BANDEL & SHINAQ, 2003: Pl. 2, Fig. 4) are common. Spines of regular sea urchins, small brachiopods, bryozoans, octocorals, calcareous sponges and some pectinids and oysters and sand with crab burrows of the *Thalassinoides* type are exposed here. Cross bedded sand and bioturbated sandstone follows, 1 m thick limestone without fossils, overlain by conglomeratic beds of 2 m and a stromatolitic limestone layer which can be correlated with the stromatolitic intercalation in gravel beds as noted in the upper part of the section east of Waqqas. The following beds consist of about 6 m of pebble deposits, a red soil separating it from about 5 more meters of such conglomeratic layers.

5 Sediments of same age to Tayba Formation east of Lake Tiberias and near Haifa

Next to Lake Tiberias on the slope to the Golan Heights MICHELSON & LIPSON-BENITAH (1986) confirmed the evidence for the Jordan Rift to have subsided since the Miocene, as was supported by and MARCUS & SLAGER (1985) based on subsurface data. At the eastern shore of Lake Tiberias deposits such as those of Tayba Formation of WETZEL & MORTON (1959) and BENDER (1968) were placed into a Tiberias Group that had been proposed by MICHELSON (1979) in his thesis. Marine Miocene outcrops in the Golan Heights according to BUCHBINDER et al. (2005) indicate a marine environment during the Oligocene. Here a near shore environment in the early Miocene and the beginning of continental conditions, in the middle Miocene was reconstructed. The lower marine 45 m of sediment of that group was called Fiq Formation and it contained foraminifera which were interpreted to have Pacific (Tethys) affinities. The following Susita Formation is characterized by shells of a Pecten-like bivalve. A conglomerate follows that was considered to belong to Hordos Formation as suggested by HIRSCH (2005). But this Hordos Formation has its type section on the other side of Lake Tiberias and thus also the other side of the Jordan transform fault. Thus close correlation across the Rift is problematic. Similar clastic deposits overlie rocks of different age including those dated as deposited during the Early Miocene and are of questionable age. The beds have been covered by flows of the Lower Basalt that according to HIRSCH (2005) has a minimum age of 9 Million years. HIRSCH (2005) found it plausible that during latest Oligocene – Early Miocene along the fracture between Arabia and the Levantine block a graben formed in which Arabia moved to the North for more than 100 km in relation to the Levantine block as had been suggested before but still he connected the formations described on the eastern side of Lake Tiberias with those found on the western side near Tiberias.

6 Oligocene-Miocene deposition within the rift proper

In Al Qarn area west of the town Abu Habil, 150 to 200 m of conglomeratic to sandy-silt-rich, rarely calcareous, and generally well bedded sediment is exposed in the steep slopes of the Wadi Al Qarn. The exact thickness of the series is difficult to evaluate due to the quite intensive faulting especially near the eastern end of the exposure. Beds may be in vertical position and also folds are present (BANDEL & SHINAQ, 2003: Pl. 2, Fig. 1).
The shallow sea deposits have formed in intertidal environment in which the sandy and muddy flats have commonly been transected by gravel-filled river channels. Synsedimentary fracturing of fine grained beds and slumping toward a general easterly direction is present as well. In the series, conglomerates are intercalated, forming especially extensive layers in the top most section exposed closest to the slope towards the Jordan River. Here they are overlain with strong unconformity by beds deposited in Lake Lisan.
The intercalated conglomerates consist of limestone gravel of large well-rounded pebbles and chert pebbles with more or less angular shape. Among these pebbles flints derived from the Eocene chalks, but from limestone with *Nerinea*-like gastropod of Cretaceous age are contained. Stratigraphically below the conglomerate are fine grained reddish sands and silts which commonly display the filling of smaller and larger channels. Fine grained deposits are often laminated horizontally or have fine cross laminar bedding. Some are bioturbated and may display the characteristic network of thalassinoid crab burrows. Some layers have mud-cracked surfaces and some are composed of desiccation shards. Two thin white chalky beds are intercalated which hold foraminifera (BANDEL & SHINAQ, 2003: Pl 2, Figs. 5–10; BANDEL & SALAMEH, 2013: Figs. 111–112) and some ostracods.

Fig. 2: The view of the Rift Valley ranges from North Shuna at the North to Waqqas at the south and from Wadi Arab reservoir to Wadi Tayba on its eastern side. Fossil bearing outcrops of Tayba Formation are found in the slope near the town North Shuna to the west of the dam and reservoir lake, along the road to the south in the foothills of the Jordan Rift, and in Wadi Tayba at the southern margin of the view that ends in Waqqas village. (Scale at lower left: approximately 3.75 km, from Google Earth 2016).

The foraminifera represent a mixture of species derived from the chalky base with Paleocene to Eocene age and are thus reworked and those from of Oligocene and early Miocene ages with good preservation. The fauna shows connections to the Pacific Ocean (BANDEL & SHINAQ, 2003; BANDEL & SALAMEH, 2013). Thus about 24 million years ago the area now occupied by the Jordan Valley in northern Jordan between Abu Habil and North Shuna was inundated by the sea coming from the north. What is now the steep eastern slope of the Jordan Rift Valley between the towns North Shuna and Waqqas at that time represented the shore. The localities known from the Golan Heights are of related age (BUCHBINDER et al., 2005) and during late Oligocene to early Miocene the sea covered much of north-eastern Jordan and reached the area between Azraq and Jafr.


Fig. 3: Limestone band (Fig. 3, left) with foraminifera and laminated, desiccated and bioturbated beds (Fig. 4, right) formed within intertidal environment in the Tayba Formation of Wadi al Qarn.

7 The land to the east

Going east from the Jordan Valley and east of the rift into the Jordanian highland (ENE of Abu Habil), to the west of Awsara village on the eastern slope canals have been eroded which are filled with gravel. Here the alluvial deposits consist of a mixture of more or less rounded brownish flint pebbles of different sizes and limestone pebbles of different size. Similar gravel and sands exposed on the Eastern slope of Jordan Valley south of Waqqas were also called Waqqas conglomerates or placed in the Shagour Formation by BENDER (1968) and as mapped by MOH'D (2000) and interpreted to be of Pliocene to Early Pleistocene age. The 10–15 m thick gravel lies on a red soil horizon of variable thickness. The basement of Paleogene limestone as well as the river deposits above it to the west of Awsara is deformed into a wide syncline and the river took its path through a wide shallow valley. Similar gravel beds overlie Cretaceous limestone east of Awsara and are exposed along the bank of the highway, here without deformation, and they agree in composition with the oldest deposits as exposed near the Jordan River in Wadi Al Qarn. It may be that the gravel of the Awsara river channel could be of the same age as that in the subsurface south of the Lake Tiberias, encountered by Zemah 1 drilling site in more than 4.000 m depth (MARKUS & SLAGER, 1985), but it may also be of much younger age. It clearly formed and was deposited prior to the strong uplift of the Jordanian highlands and prior to the erosion of the deep valleys which usually end at the base of the Ghor.

8 First salt deposits in the Rift Valley: the Rift before the Messinian

Deposition of sediments of a saline environment started early in the rifting process during early Miocene (BANDEL & SHINAQ, 2003). The exposure near Waqqas has cyan bacterial crusts in the upper gravel bed indicating that salinity began to deviate from that of normal sea water and changed to higher salinity until it came to the deposition of saline sediments consisting of an intercalation of halite, gypsum and dolomite. Later the more solvable layers were partly leached again leaving the dolomite layer in the shape of the characteristic cellular dolomite. The period from these deposits of saline environment through the later Miocene until influence of the refilled Mediterranean Sea at the end of the Miocene and the beginning of the Pliocene has not been recognized up to date in sediments encountered in the Jordan valley.

SCHATTNER et al. (2006) suggested the presence of a Qishon-Sirhan Graben that formed alongside or prior to the Dead Sea fault- with saline deposits of the Miocene in it. Here the Qishon Yam 1 well drilled at a water depth of 102 m on the edge of the continental shelf about 20 km northwest of the city of Haifa penetrated a thick sequence of sediments including a marl with intercalated anhydrite dating from the mid-Oligocene to early mid-Miocene. This sequence is bounded by two unconformities from above and below. It overlies Late Cretaceous rocks and is covered by early Pliocene sediments. The age of the deposits was determined with foraminifera. Accordingly, deposition occurred in shallow water and under sabkha-like conditions at mid-Oligocene to early mid-Miocene times. SCHATTNER et al. (2006) interpreted the area of deposition as part of the Qishon-Sirhan failed rift that was

reconstructed as Qishon-Sirhan Graben that formed alongside or prior to the Dead Sea fault and accumulated saline deposits of Miocene age. But its existence is still somewhat doubtful.
A borehole (Zemah 1) drilled just south of Lake Tiberias west of the Jordan River of almost 4.250 m depth (MARKUS & SLAGER, 1985) documented that below gravel and sand much of the core consisted of salt. The initial Rift Valley received sediments derived from the rift margins, predominantly from the Eastern highlands. The Dead Sea Basin formed a depression supposedly during the early Miocene (HOROWITZ, 1979, 2001; GARFUNKEL & BEN AVRAHAM, 2001; GARDOSH et al., 2008). Clastic sediments of the Miocene Hazeva Formation were deposited here by a river system supposed to have flown across the Dead Sea Basin. It is thus interpreted to indicate that during this period (late Miocene) sedimentation and subsidence kept pace and that the flanks of the basin did not form topographic barriers (GARFUNKEL, 1997).

9 The Messinian stage and proposed Beisan Canyon

During most of the highest Miocene the Mediterranean Sea was cut off from the Atlantic Ocean. The Mediterranean Sea formed an enclosed basin in which the sea water evaporated during the Messinian stage which lasted for about 700.000 years. Thus large parts of the former sea bottom became dry land (HSÜ, 1972; GOVERS, 2009). During this Messinian stage the Levantine Basin of the eastern Mediterranean Sea contained a huge salty lake resembling the modern Dead Sea but of much larger size. In the Levantine Basin the Messinan salt is up to 2.000 m thick found now at 2.000–3.000 m below sea level (HÜBSCHER & NETZEBAND, 2007; HÜBSCHER & DÜMMONG, 2011).
A deep valley or canyon can have become eroded that extended from the Mediterranean Basin near modern Haifa to the Jordan Rift Valley (BANDEL & SALAMEH, 2013). We assume that this Beisan Canyon connected the Jordan Rift Valley with the low area in the Levantine Basin bridging the 3.000 m difference in level into the Mediterranean Basin. The reconstruction of GVIRTZMAN et al. (2011) allows the model according to which the sea with begin of Messinian age left Galilee. Its presence there during the Late Miocene has not left good evidence that is documented. Thus the remaining depression between the continental margin and the northern Rift Valley may have been transformed into a deeper valley leading into the Qishon canyon on the continental slope (GARDOSH & DRUCKMAN, 2006; GARDOSH et al., 2008). Thus a hypothetical Beisan Canyon may have been eroded and formed a connection to the Jordan Rift and diverted rivers coming from the eastern Arabian platform to flow down slope into the Levantine Basin. By that process a canyon may have been eroded that may later have served as the way by which the Lago Mare Fauna with origin in the Paratethys entered the Rift. River canyons forming during the time when the Mediterranean Basin contained little or no water have been documented in case of the Nile (BARBER, 1980) or the Rhone. The Lago Mare fauna can have climbed up in the fresh water of the rivers. Later, during the Zanclean flood the Beisan Canyon can have permitted the flow of brines from the Levantine salt lake into the Jordan Rift Basin. It is thus assumed to have been the way on which the characteristic fresh water molluscs entered Jordan being members of the Lago Mare fauna, and afterwards it served as channel for very salty water derived from the salt lake in the Levantine Depression during the Zanclean flood representing the origin of the salts of the Dead Sea.
During the Messinian Salinity Crisis (Messinian Event), and in its latest stage the Lago Mare event the Mediterranean Sea went into a cycle of partly or nearly complete desiccation (HSÜ, 1972) throughout the latter part of the Messinian age from 5.96 to 5.33 million years ago. It ended with the Zanclean flood, when the Atlantic reclaimed the basin (ROVERI et al., 2008). 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 3.000 m below sea level (RYAN, 2009). With this deep trough the canyon at the Beisan valley may have established a connection of the Jordan Valley Basin area to the Mediterranean Sea Basin. Such a connection was also interpreted to have connected the Mediterranean Sea with the Rift Valley by GARFUNKEL (1988) referring to NEEV & EMERY (1967) and MARKUS & SLAGER (1985), also accepted by FLEXER et al. (2005). The huge amount of salt as encountered in bore holes downstream of Lake Tiberias and under the Dead Sea itself may well have been derived from the deep-lying Levantine salt lake that lay up to 3 km below modern sea level (HÜBSCHER & NETZEBAND, 2007; HÜBSCHER & DUMONG, 2011). From the African Continent the Nile had dumped a lot of sediment into that Levantine depression, covering it largely with sand that came down the long Nile Canyon, which extended far upriver (BARBER, 1980; HARMS & WRAY, 1990). Thus fresh water can have flowed across the former salt flats which were at least partly covered by the alluvial deposits derived from the Nile.

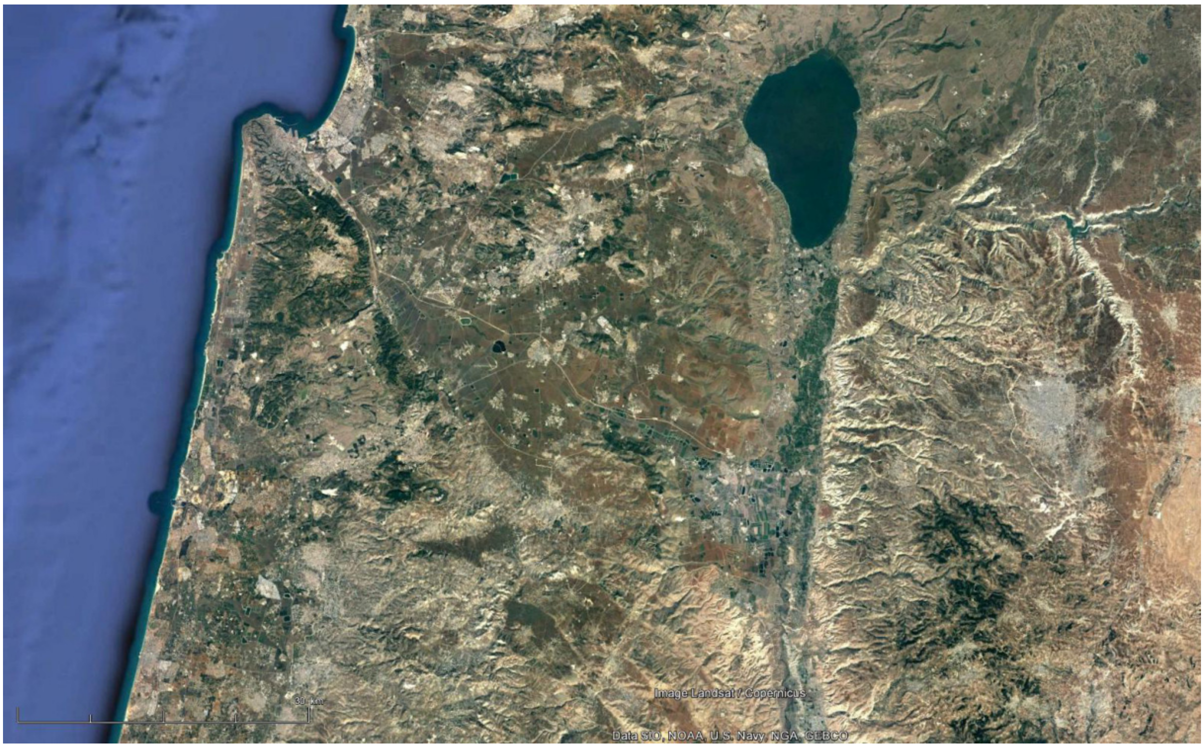


Fig. 5: A Beisan Canyon may have been present between Haifa in the West and the Rift Valley with Lake Tiberias and it could have been eroded by the water of the Yarmouk catchment collected from the eastern lands connected to the Sirhan depression in the east. Towns seen are Haifa on the Mediterranean Sea shore and Irbid on the Jordan highland. The canyon would have crossed Galilee north of the Carmel fault and the water coming from the east used different pathways as those seen now in the Wadi Yarmouk, Wadi Al Arab west of Irbid and Wadi Ziglab and Wadi Yabis west of the Ajlun, which have been carved into the slope much later. (scale 33 km, from Google Earth 2016)

10 The possible influence of the Lago Mare fauna

In the Lago Mare Facies of the Mediterranean Basin molluscs and ostracods established themselves 5.52 to 5.33 million years ago (ORSZAG-SPERBER, 2006). Characteristic organisms for the fresh water of the Mediterranean at that time are the mollusks *Dreissena, Melanopsis, Melanoides* and *Theodoxus*. All these molluscs have been recognized to have lived in the Jordan Valley since begin of the Pliocene (BLANCKENHORN & OPPENHEIM, 1927; TCHERNOV, 1975, 1988). With the exception of *Dreissena* they still represent the characteristic species living in the fresh water of Jordan. *Melanopsis, Melanoides* and *Theodoxus* from Al Qarn Formation are related to the species which lived in Lakes on the Island of Kos and Rhodes during Pliocene times (WILLMANN, 1981; BANDEL, 2000, 2001). Also CLAUZON et al. (2005) suggested that after the Messinian stages pathways for molluscs such as *Melanopsis* and *Dreissena* may have existed from the Paratethys and even reached to the Tiberias region. *Melanoides* is nowadays usually found on muddy ground, and that was the same on the limy mud in the ponds that formed Aramshi Formation. In case of *Melanopsis* and *Theodoxus* of Al Qarn Formation some have characteristic shell shapes compared to the species of later times (ALHEJOJ & BANDEL, 2013), including those which lived in and on Bakura River and in and on the Jordan River when its water was still clean.

11 Amora Salt deposition

During the Zanclean flood the Mediterranean Basin was filled with sea water coming from the Atlantic Ocean again and the salt water that flooded the Mediterranean Sea also entered the Rift Valley (BLANCKENHORN, 1929). We assume that it used Wadi Beisan on its way into the Jordan Rift Valley. The level of the bottom of the rift at that time lay below the new sea level of the Mediterranean Sea and sea water entered the rift valley. A connection to the Zanclean flood 3.6 Million years ago was suggested by BANDEL & SALAMEH (2013) and also by KIRO et al. (2015). Much of the sea water evaporated leaving thick layers of salt (NEEV & EMERY, 1967; MARKUS & SLAGER, 1985). In the deeper parts of the Rift lakes of sea water formed the Sedom Lagoons and evaporated. Less salt was

deposited in the northern depression of the Lake Tiberias region and more in the southern depression of the Dead Sea. The southern depression extended north up to the Karama area. North of the Dead Sea proper salt deposits were subsequently covered by terrestrial deposits.
Sedom Formation (also called Amora or Gomorra) was termed by WYLLIE (1931) and defined by ZAK (1967). Its base is unknown and it consists of rock salt with lamina of silt and gypsum. In the Dead Sea basin it may lie to almost 10 km below surface (GARFUNKEL, 1988). It has an outcrop in Mount Sedom on the western side of the Dead Sea that represents a salt-dome.
NEEV & EMERY (1967) considered Sedom Formation to represent a Pliocene rock salt that unconformable overlies the conglomerates of Hazeva Formation and is suggested to be 1.500 to 2.000 m thick. But BENDER (1968) reported on a drilling operation carried out from the Jordanian Lisan Peninsula that encountered more than 3.000 m of salt before it stopped still within salt. It is intercalated with gypsum and 75% of it is salt.
The Sedom lagoon was fed from the open sea, and according to the interpretation of TORFSTEIN et al. (2009) it became a terminal lake around 3 Million years ago. WALDMANN et al. (2009) dated the upper boundary as lying at the base of Eem interglacial times with sediment derived from cores. STILLER et al. (2009) assumed that the Dead Sea Rift was intermittently connected to the basin of the ancient Mediterranean Sea for a time of about 1 million years. They suggested that the Neogene incursion resulted in the formation of the Sedom marine lagoon with deposition of thick evaporate sequences near the Dead Sea and south of Lake Kinneret as noted by MARKUS & SLAGER (1985).
We here suggest that much of the water that entered the Rift and filled its depressions was derived from the Levantine salt lake and thus was brine that contained more salt than is usually present in sea water. During the Pliocene, the connection with the Mediterranean Sea ended and the Jordan valley became a land-locked depression with lakes of varying sizes developed in it. Since then, sedimentation has lagged behind subsidence, leaving a deep topographic depression with deposition of fluvial and lacustrine sediment and evaporates.
After disconnection from the sea, sediments continued to accumulate in the subsiding Jordan Rift - Dead Sea basin. The salt lakes may have been continuously recharged by runoff water and brines, and mainly aragonite, gypsum, and halite was precipitated (STEIN et al., 1997; TORFSTEIN et al., 2008). The salt water mixed with carbonate rich water from rivers and ground water predominantly coming from the rising eastern land. As the Sedom lagoon was disconnected from the open sea, as was assumed to have occurred around 3 Million years ago succeeding the Zanclean flood, the water body became a terminal lake (TORFSTEIN et al., 2008, 2009, 2013). The salt of an older Sedom Formation is difficult to distinguish from that of a younger Amora Formation, thus these formations can be viewed as one. WALDMANN et al. (2009) determined the end of Amora deposition at around 135.000 years ago with a lake level of around 380 m below modern sea level. Thus from the Messinian Sedom lagoon to the Samra Lake more than 2 Million years have to be accounted for. The age determination of Lake Samra deposits based on U-Th dating of aragonite was carried out by WALDMANN et al. (2009) and both deposits consist predominantly of reworked Mediterranean salts.

12 Old Fresh water deposits in the Northern Rift, Ubeidiya, Erk el-Ahmar, Al Qarn Formations

Gesher Formation was recognized in the northern Jordan Valley next to Lake Tiberias and interpreted to overly Messinian and post Messinian sediments and to predate the Cover Basalt (SCHULMAN, 1962). HOROWITZ (1979) suggested an age of more than 1 Million years, to Gesher Formation, while HELLER & SIVAN (2001) assumed an age of 780.000 thousand years. The Ubeidiya, Erk el-Ahmar, and Al Qarn Formations have been interpreted to be younger in age, but their isolated outcrops do not allow locating their exact place in a succession and they may all have been deposited more or less contemporaneous.
Ubeidiya Formation is about 30 m thick and consists of alternating lake and river deposits in strongly inclined position (HOROWITZ, 1979, 2001). Its depositional environment has been interpreted to represent a river discharging into a lake with swamps (HIRSCH, 2005) and its exposure lies 3 km southwest of Lake Tiberias (SCHULMAN, 1962). Layer with *Melanopsis* are followed by conglomerates holding implements produced by ancient man. 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 and according to BENDER (1968) bones determined by HAAS (1961, 1963) also belong to *Archidiscodon*, *Stegodon*, *Hipparion, Giraffa, Cervus, Sus, Ursus*, and more. It was dated to up to 1.4 Million years old or older than 700.000 years by HOROWITZ (1979) (much less by HELLER & SIVAN, 2002). It forms an angular unconformity with Bakura River beds and Lisan Formation.
Erk el-Ahmar Formation is exposed southwest of the confluence of the Yarmouk River into the Jordan River (TCHERNOV, 1975; HOROWITZ, 1979). BLANCKENHORN (1912) considered it to belong in his *Melanopsis* Stufe together with the Ubeidiya Formation, and BLANCKENHORN & OPPENHEIM (1927) studied some of its fossils. Some 80–90 m of clay and marls are tilted with strata dip of 25° to 40° to the east and disappear under the Jordan River. *Dreissena* is restricted to only this location and *Theodoxus* resembles those still found in Jordan, with

varieties from such with smooth shell but also keeled ones as live in the northern Ghor canal until nowadays. Also *Viviparus* was recognized from Erq el-Ahmar which is not known from Jordan and closely resembles species living in the Nile system. *Viviparus* was also a member of the Lago Mare fauna and can have been derived from it.

Al Qarn Formation is exposed at the eastern banks of King Abdulla Canal to the west of Abu Habil (southern part of the town Masharia) and to the south of Jebel al Qarn (Figs. 6 & 7). Here it overlies the Oligocene–Miocene deposits of Tayba Formation with an angular unconformity. The lake and river deposits of Al Qarn Formation are tilted towards the west (Figs. 8 & 9) and displaced due to the movement along the Jordan transform fault. The top of the formation holds among the fluviatile gravel a bed predominantly composed of calcareous pisolite pebbles. These have been deformed by pressure that developed during the formation and reshaping of the Jordan Rift (BANDEL & SALAMEH, 2013: Fig. 113). Such pisolites had formed in the soil that covers the chalky-limy deposits of the Late Cretaceous and Early Paleogene sediments which are found in the eastern slope of the Rift Valley nearby and had been washed out by strong rains and added to the alluvial gravels of Al Qarn Formation in more or less distinct layers, the upper of which near and south of the bridge being especially extensive. Into the sequence of predominantly alluvial gravel that is exposed along the canal to the north of the bridge where the canal crosses over the road fossil bearing beds of approximately 25 m in thickness are intercalated. The fauna consists predominantly of freshwater and land-mollusks as described by BANDEL (2000, 2001, 2010); BANDEL et al. (2007) and ALHEJOJ & BANDEL (2013). The fossil bearing beds have a dip with about 50° towards west and are partly consolidated by calcareous cement. In the beds with well preserved fauna the sand is still unconsolidated and no dissolution of shells took place, aragonite shell substance is still preserved and no cement was formed. The most conspicuous fossil is *Melanopsis* that is preserved without changes in one layer, while in the next layer it may be found as cavities in consolidated sandstones. The molluscs hold besides small bivalves of the *Pisidium* type and rare badly preserved shells of *Unio*, several species of *Melanopsis* in addition to *Theodoxus, Melanoides, Bithynia*, and several small hydrobioids, *Ancylus, Gyraulus* and *Valvata*. A variety of stylommatophoran pulmonate species and the caenogastropod *Pomatias* were washed into the lake and had formerly lived near it on land. Fragments of larger bones as well as teeth of crocodiles occur. Ostracods and remains of crab claws were present as well. The fresh water crab *Potamon* is still living in most creeks and rivers in Jordan, as amphibious animal with rapid movement on land as well as in water.

The difference to the fauna of Erq el-Ahmar Formation may indicate differences in the environment, since *Viviparus* and *Dreissena* are not found in the Al Qarn fauna. Their living representatives use phytoplankton as food which they filter from the water. Thus their presence may reflect that the water in the Erq el-Ahmar consisted of ponds and lakes richer in nutrients than that of the Al Qarn ponds. Most gastropods encountered in Al Qarn Formation have living relatives in Jordanian fresh water creeks and ponds.

Fig. 6: Lake Al Qarn freshwater deposits with *Melanopsis* exposed next to the Ghor Canal south of Jebel al Qarn. The documented gastropod *Melanopsis* is 12 mm high. Exposure with fossils as in Fig. 6 (left) is next to the white rocks next to the canal margin, and above and below are gravel beds. The canal (Fig. 7, right) is also seen in Fig. 10.

Figs. 8 (left) & 9 (right): Intercalation of gravel and red sand-soil of the Al Qarn deposits with relatively poorly sorted material as it overlies the fossil bearing beds on the eastern margin of King Abdulla canal.

Fig. 10: Area of Al Qarn sill with the town Ausara on the in the NE corner. Wadi Al Qarn joins the Jordan Zor at the southern margin and Beisan town lies close to the ponds seen in the upper left corner (western corner). (scale 43 km, copy from Google Earth 2016). Wadi Al Qarn lies in the SW corner and arises from the Ghor just above (East) of the King Abdulla Canal at the point of it crossing the road with a bridge. The Wadi Al Qarn ends at the margin of the Zor and exposes Tayba Formation (Figs. 3 & 4). Al Qarn Formation is exposed along the canal between canal bridge and road bridge on the eastern slope of the excavation of the canal. This canal follows the upper margin of the Ghor next to the slope (Katar) to the Zor.

13 Volcanic Rocks

Late Tertiary and Quaternary basalts cover large extents in northeast Jordan. Bender (1968) recognized six phases of basalt flow in north-eastern Jordan. Garfunkel (1989) and Weinstein et al. (2006) suggested that the Dead Sea Transform-associated volcanism is related to crustal/lithosphere drainage of magma with the rift functioning as a plumbing system, allowing access of magmas to the surface. Late Miocene basalts erupted to the west of the Rift in several localities of Galilee (Shaliv, 1991). Thick basalt flows locally fill parts of the Yizre'el valley, and it was thus suggested that the Yizre'el Qishon rift formed during the middle to late Miocene and accumulated sediments and volcanic rocks. Their flows interfinger locally with sediments which have been interpreted to have formed during the Messinian and following Zanclean stage of the dry Mediterranean basin and its filling again by the sea coming from the Atlantic Ocean. The conglomeratic Hordos Formation with type location at Mount Hordus 1.5 km south of Tiberias are intercalated with basalts and basaltic pebbles mixed with limestone pebbles of Eocene and Cretaceous (BENTOR, 1963). It is locally up to 400 m thick (SCHULMAN, 1962). A younger volcanic phase is responsible for the Cover Basalt, which is of post-Messinian age as has been determined by 40Ar/39Ar age as erupting between 5 and 3.5 Million years ago (HEIMANN et al., 1996). The same age is from the Plateau Basalt at Um Qais. SHULMAN et al. (2004) noted numerous basalt flows which cover most of the elevated Golan plateau. They piled up to reach locally more than 1.000 m in thickness and are part of a huge basalt field that occupies vast areas of SW Syria and NW Jordan and continues into the volcanic range at the margin of Sirhan depression. These Harrat Ash Shaam flood basalts covered large parts of Jordan and Syria (TARWNEH et al., 2000) with a small extension toward northern Israel. When this event crossed the Dead Sea Transform it also produced volcanic rocks and magmatic intrusions as have been noted in the Zemah-1 borehole within the rift's down-faulted blocks (INBAR, 2012). Thus the oldest basalt is that in Galilee erupting in the Late Miocene, the next is the Cover basalt which may be similar in age to the basalt that intruded into the Amora salts below the northern Rift just south of Lake Tiberias during the Pliocene.

The age determination of volcanic eruptions may allow to date the time at which the Jordanian Highland rose up. It was nearer to the level of the Rift Valley floor when Um Qais and Mujib basalts were produced and it was high up at the level of today when the latest Yarmouk and latest Zerka Main lava streams flowed. These streams flowed in valleys which had been excavated before or during the existence of Lake Lisan. The basalts in the upper valley of the Zerka River were produced when that valley was in the process of erosion since they covered a terrace, well exposed a few km west of the treatment plant of Amman and below two distinct basalt flows (Besancon & Sanaville 1988). The basalt connected to Armashi Formation and that covering Ghor al Katar deposits can be of similar Pliocene-Pleistocene age, and those erupting into the Yarmouk gorge and the Zerka Main gorge belong to younger eruptions, partly of Holocene age.

The basalt that covered the region of the Mujib Valley before the erosion of that deep canyon probably erupted around the same time as the cover basalts of the Golan and the Um Qais plateau. BLANCKENHORN (1912) described it and noted its eruption prior to lava flows found in the Wadi Zerka Main. The later is about time equivalent to the lava flow that descended from the east to the rift valley along the gorge of the Yarmouk River. This Yarmouk Basalt is around 66.000 years old (HEIMANN & BRAUN, 2000) (or 70.000 according to NRA map). Younger Basalt is present in the Yarmouk valley as Raqqat Basalt on the valley flanks.

In the Jordan Valley proper only small outcrops of volcanic material are present such as a few km north of Waqqas below Aramshi hill (MOH'D, 2000 a & b) and at Ghor al Katar near the Karama Reservoir. BENDER (1968) noted that the basalt formed connected to the alluvial deposits of Ghor Al Katar Formation was present before deposition of the Lisan Formation. This later basalt may have erupted at approximately the same time as that of the basalt plug (Tall al Muddarwar) that underlies Aramshi Formation.

The catchment area including Wadi Sirhan became blocked by Huran and Harrat esh Sham basalt flows. These volcanic materials blocked water from reaching the Jordan Valley area (SALAMEH & FARAJAT, 2007). This huge catchment was able to provide all the sediments which compose the Bakura Formation and afterwards the basaltic eruptions of Huran and Harrat esh Sham blocked the drainage of Damascus, Hammad, and Sirhan basins from reaching the Jordan Valley area. Lisan Lakes may have received its water also from the drainage basins of Damascus, Hammad and Sirhan. The Harrat esh Sham basalt cover extends to Damascus in the north, to the Yarmouk and Zarka Rivers in the west, far into Hammad basin in the east (300 km E–W extension) and far to the south into Saudi Arabia.

Fig. 11: On the southern margin of Zerka Ma'in the upper basalt cover is exposed into which the pre-Lisan valley of Zerka Ma'in was eroded. It had been filled again to Lake Lisan level and the modern valley has been cut into that fill. The Dead See and its western shore form the background. The black basalt is seen in Fig. 12 at the southern margin.

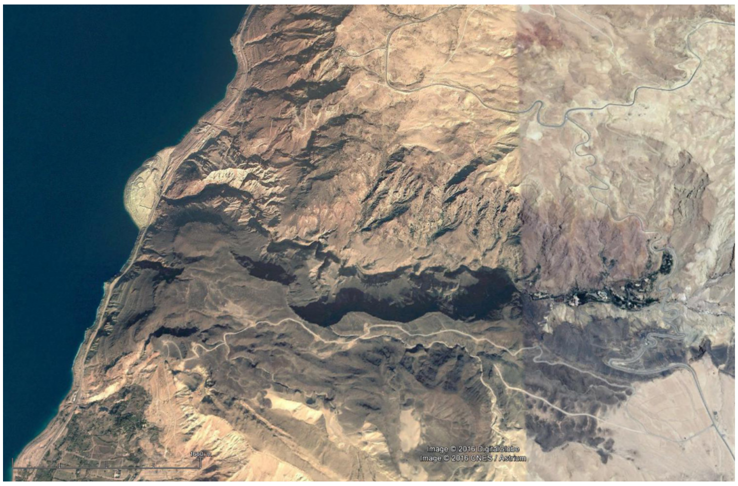


Fig.12: Dead Sea at left and Wadi Zerka Ma'in central and Cambrian-Triassic sequence with Cretaceous top at the northern part. The dark rocks are basalt of different flows, into the upper one the valley was cut and partly filled with gravel during existence of Lake Lisan. Picture on Fig. 11 was taken from the road on the southern margin of the wadi. Herodes bath and the hot springs lay on the shore of the Dead Sea next to the scale.

Fig. 13: Tall al Muddawar is composed of the limestone of Aramshi Formation and had provided the locality of an ancient village and preserves an older former level of the Ghor. The modern village Aramshi lies just south of it and the Ghor canal is present next to the main road to the west that leads from North Shuna to Masharia.

14 Aramshi Formation deposits

Aramshi Formation forms a flat carbonate rock plate building the top of Tall al Muddawar, about 2 km north of Waqqas (BANDEL & SALAMEH, 2013). This Aramshi Formation is a carbonate deposit forming the hill that rests on the top of a small truncated basalt sill. The massive solid limestone at the base contains 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 a massive solid limestone with traces of roots and Stromatactis-like structures as well as pisolites. Stromatactis is a cavity filling that usually consists of layers of calcite crystals forming the top and filling part of the cavity and with sediment of horizontal stratification in the basal part. Prior to the formation of stromatactis the cavities formed by the disappearance of a part of the former sediment when strata had been sufficiently consolidated leaving hollow spaces. These cavities were filled afterwards by deposition of particles settling from water still percolating through the forming rock and later by cement crust deposited as concentric layers closing the remaining cavities.

The whole deposit has been surrounded by Lake Lisan with Tall Muddawar forming an island composed of the solid carbonates of Aramshi Formation.

The age of the Aramshi Formation is unclear and it is probably younger than Al Qarn Formation but it is clearly older than Lisan Formation and its beds are weakly inclined towards the west while the Lisan Formation nearby is horizontally stratified. The depositional environment is that of a clear shallow lake or pond provided with water from springs and with pisolites forming due to the motion of carbon rich water. The lake had a bottom consisting of pure carbonate which was the living environments of mollusks as are still living in clean fresh water in Jordan. This fine mud was transformed into a very solid and hard limestone by diagenesis.

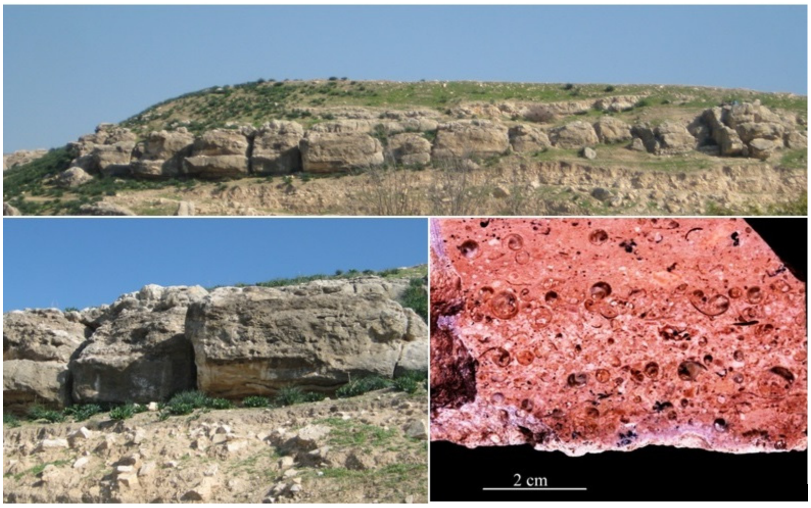
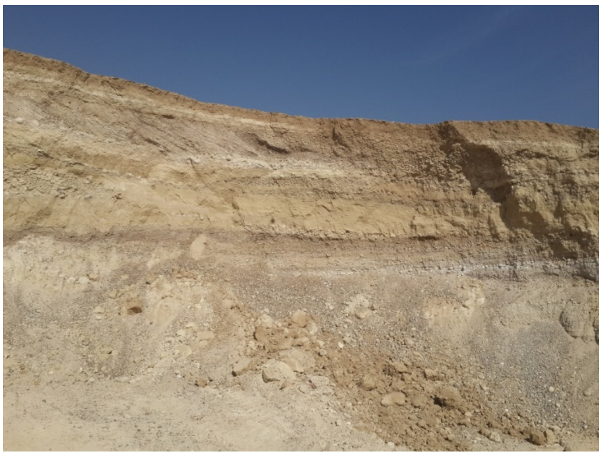
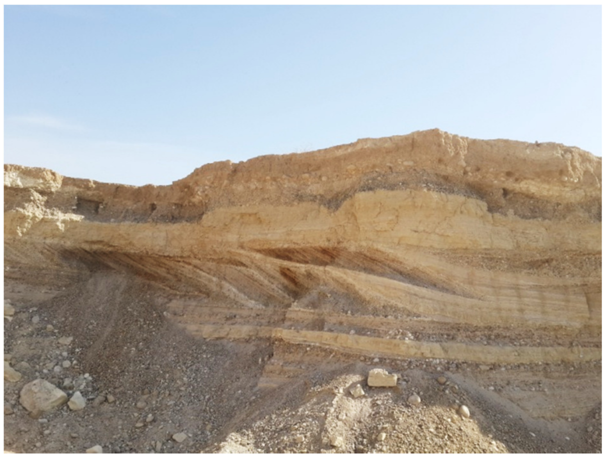


Fig. 14: Upper – Tall al Muddawar north of Aramshi town is a hill with an almost flat carbonate rock plate that has a slight dip to the NW. Left – Aramshi Formation is composed of massive solid limestone beds. Right – polished section of the limestone documents freshwater gastropods including *Theodoxus, Melanopsis, Melanoides* and small planorbids which lived in Aramshi Lake.

15 Ghor al Katar

A Ghor al Katar series is documented by Bender (1968: Fig. 94). Just west of the Karama reservoir dam site the Ghor al Katar Formation dips strongly toward the west. Abed et al. (2004) described the Ghor al Katar Formation as forming a 350 m thick section consisting of coarse grained sediments. They suggested that it has been deposited in a fresh water lake sometime during the Early Pleistocene. They noted that this sequence consists of 28 cycles each of which consists of thick conglomerates, sand and silt beds, and red soil. The Ghor al Katar sequence closely resembles the alluvial gravels which contain the fossiliferous portions of the Al Qarn Formation and may well be of similar age. It was deposited by a river and was deformed subsequently and now lies on the top of a salt dome that has been pushed up since the existence of Lake Lisan and is still rising. An olivine alkali basalt dyke is present and lies perpendicular to the sediment covering it as was shown by Bender (1968). This basalt may be of similar age as that underlying Aramshi Formation. The younger sediments of the Lisan and Damya Formations of the uppermost Pleistocene overlie the Ghor al Katar sequence with angular unconformity.





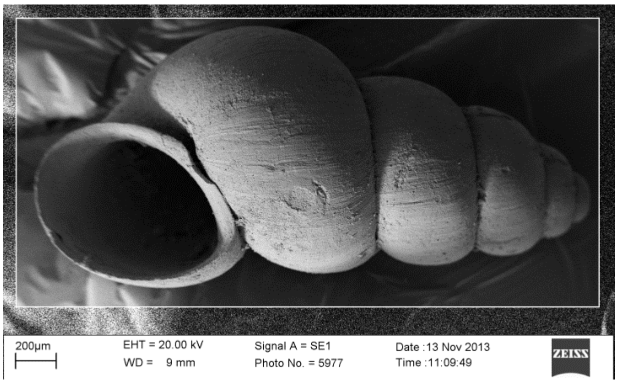
Figs. 15 & 16: Lisan deposits are intercalated and overlain by Damya Formation with cross bedded beach and gravel filled canal next to it exposed in a quarry west of the dam of Karama Reservoir. Thus Damya Formation sediments here are time equivalent to Lisan Formation sediments, representing the deposition near to the shore and here in the outcrop with the shore. Fig. 15 (left) has cross bedded beach deposits next to gravel filling a former channel that runs parallel to the beach, (upper part of quarry wall show in the picture). Figure 16 (right) documents inclined gravel beds formed on a beach, over and underlain by laminate lake deposits and covered by terrestrial beds.

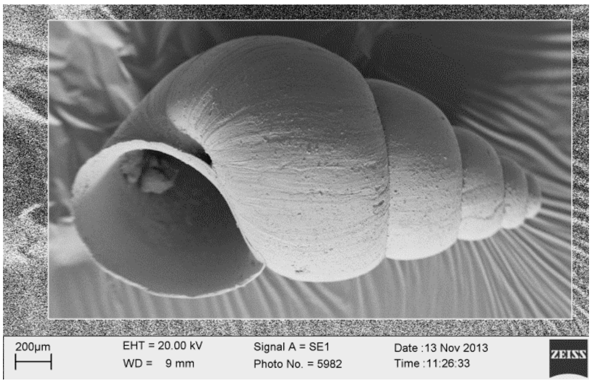

Figs. 17 & 18: Same quarry as in Figs. 15 and 16 with reworked Ghor al Katar conglomerate is intercalated in laminated Lake Lisan deposits. The deposits have formed in the region of Lake Lisan in which the salt dome pushed periodically up and exposed Ghor al Katar gravel to erosion and the shore of the lake with transition to terrestrial deposits with intercalated fluvial channels. Fig. 18 (right) is close-up of Fig. 17 (left).

Fig. 19: The dam of the Karama reservoir with Ghor al Katar sequence at the western margin of the lake and the northern top of a salt dome is shown. The meanders of Jordan River are at the west of it and the Karama reservoir lies to the NE of it and updoming salt is also west of the creek that issues from the lake. Exposures at the northern end of the Ghor al Katar layers provided the sections seen in Figs. 15–18.

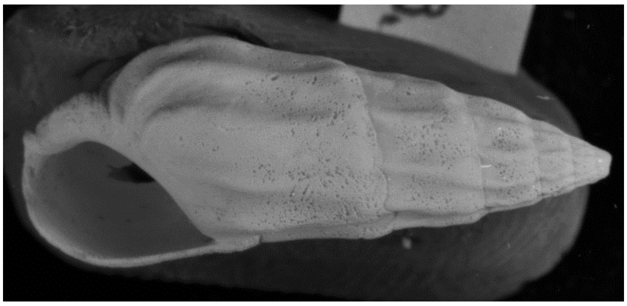
16 Bakura River deposits

Bakura Formation had originally been named by NOETLING (1886) “Bakura Schotterstufe”. It consists of river gravels conspicuously containing *Melanopsis* and underlies the laminated deposits of Lake Lisan. PICARD (1932) also recognized the formation from Bakura as exposed near the conference of the Yarmouk River into the Jordan River. BLANCKENHORN & OPPENHEIM (1927) reported species of *Melanopsis* from that area and called the deposits containing it the “*Melanopsis* Stufe”. River gravel with *Melanopsis* are also exposed along the steep slopes of the Zor from west of the Al Qarn Ridge to near Deir Alla. Here the Zor exposures of fluvial sands, gravels and marls locally contain many fossils of fresh water molluscs. The Bakura River also eroded into deformed Al Qarn Formation and the even more deformed Tayba Formation close to the Al Qarn ridge. The river discharged into the Samra Lake (Paleo-Dead Sea) and it was not connected to the Hula Basin since the Tiberias Basin according to HAZAN et al. (2005) and SCHATTNER & WEINBERGER (2008) was not in contact with the Hula Basin. Thus the recent Jordan River and ancient Bakura River probably had different sources. The bulk of the water of Bakura River was probably derived from the east and northeast getting its water from the older drainage system which included the Damascus, the Hammad and the Sirhan Basins, before the blocking of much of it by the Hauran and Harrat es Sham basalts (SALAMEH & FARAJAT, 2007).





Figs. 20 and 21: Varieties of *Hydrobia* sp. from Bakura Formation near the mouth of Wadi Al Qarn.



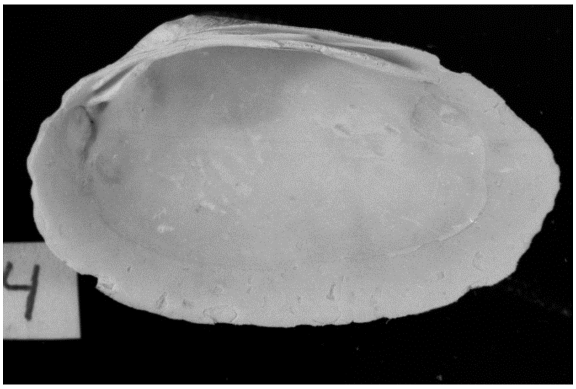
Figs. 22 & 23: *Melanopsis noetlingi* (22: left) and the similar *Melanopsis blanckenhorni* (23: right) from Bakura Formation with approximately 15 mm long shell.

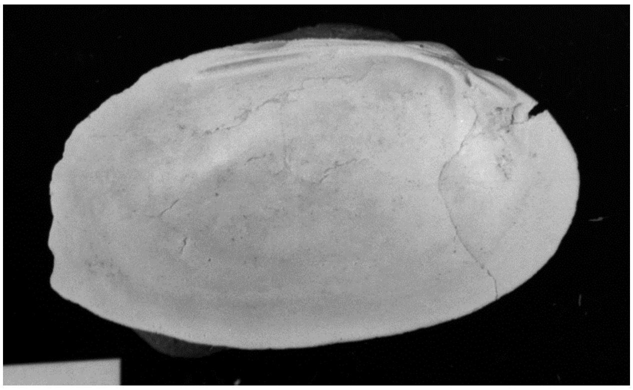
Among the molluscs that lived in Bakura River two species of *Unio* and *Theodoxus jordanicus* resemble the species surviving today in the waters of the Jordan Valley and are still living in the northern Ghor canal. Among *Melanopsis* BANDEL (2000) recognized 6 species that lived in Bakura River, *Melanopsis buccinoidea* FERUSSAC, 1823, *Melanopsis costata* FERUSSAC, 1823, which live creeks as well as *Melanopsis noetlingi* BOURGUIGNAT, 1886, *Melanopsis saulcyi* BOURGUIGNAT, 1853, *Melanopsis jordanica* (ROTH, 1839), and *Melanopsis blanckenhorni* SCHÜTT, 1988 (BANDEL, 2000: Figs 97–103). *Melanopsis buccinoidea* from the Bakura River is close in shape to the most common variety or species of *Melanopsis* which is still found in Jordan (BANDEL, 2000: Figs 20–24). The smooth shell consists of 8 to 9.5 whorls and can grow 25 mm in height and 12 mm in width with pointed spire and rounded body whorl. *Melanopsis costata* has a more slender shell with up to ten whorls with 12–15 straight ribs which continue onto the base. *Melanopsis noetlingi* has a conical spire and with pronounced suture and narrower ribs than are developed in the living *Melanopsis costata*. *Melanopsis saulcyi* has axial ribs as well as some spiral elements on its whorls and the shell is approximately 15 mm in height smaller than *Melanopsis costata* and has a shorter spire (BANDEL, 2000: Figs. 78–79, 84). *Melanopsis jordanica* has a short shell with rounded whorls and simple solid axial ribs from top at the suture and to the base (BLANCKENHORN, 1896, 1912; BANDEL, 2000, Figs. 127–128).

The gravel beds of Bakura Formation contain channels which may in part be filled with mud that may be calcareous and may hold minute pisolites resembling oolites. Some layers hold shell debris consisting of *Hydrobia* representing an environment of lightly salty water during its growth.

The gravel fans coming from the East derived from creeks that entered the Jordan Valley often reached almost the center of the Valley and thus the margin of Bakura River. This situation differs from the condition as it is nowadays where fans of debris only reach the margins of the Jordan Rift Valley and remain in the Ghor but not the actual area of the Zor. While gravel coming from the highlands by the tributaries merged with the gravel transported by Bakura River this is not so with modern Jordan River which it reached only by the gravel transported by the Yarmouk River and by the Zerka River. The Bakura River, therefore, in the times before being flooded by Lake Lisan flowed in a more deeply excavated valley with a more concave shape as is present now in case of Jordan River and with debris fans of its side creeks advancing to the margin of the river (BANDEL & SALAMEH, 2013). This situation can also be interpreted as representing a time span during which more erosion on the highlands resulted in larger gravel fans deposited in the Jordan Valley, which therefore reached the river. Nowadays the Jordan River erodes its bed predominantly into Lisan and pre Lisan-deposits and thus the top of Bakura Formation.

Coarser debris of creeks and rivers coming from the highlands are deposited on the margins of the Jordan Valley plain quite some way from the Zor plain. Gravel filled river flow channels are exposed along many wadis especially south and west of Irbed and along the roads to Amman and North Shuna. The age of these river beds has not yet been well established and they may be age equivalent to the gravel composing much of Al Qarn Formation and they are older than Lake Lisan. When Lisan Lake formed the eastern valleys had been more deeply eroded than the older gravel filled river channels exposed on the highland.





Figs. 24 & 25: The bivalves cf. *Unio semirugatus* LAMARCK, 1819 (24: left) with rounded shell and *Unio terminalis* BOURGUIGNAT, 1852 (25: right) with more elongate shell of about 4 cm in size from Bakura Formation. The two species of Unio are found near the mouth of Wadi Al Qarn.

Figs. 26 (left) & 27 (right): Gravel fan coming from the side entering and merging with the Bakura river gravel beds. Finely laminated Lake Lisan deposits overly the gravel of Bakura Formation

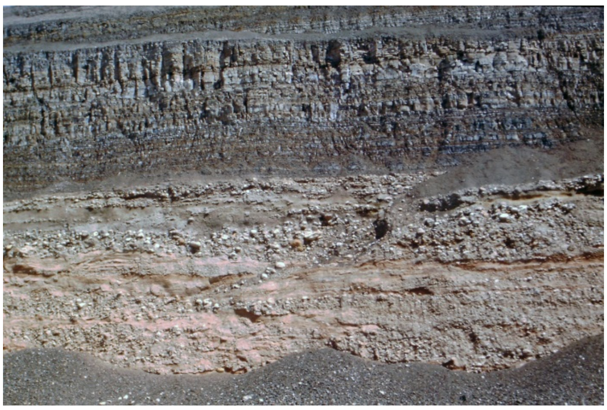


Fig. 28: Bakura River gravel is covered with laminated Lisan Lake deposits stemming from a creek that issued into the lake nearby.

17 Samra Lake

Bakura River entered Samra Lake, just as Jordan River now enters the Dead Sea. Samra Formation was first described in the Jericho area north of the Dead Sea as fluvio-lacustrine deposits (PICARD, 1943). The outcrop underlies the Lisan deposits contrary to the opinion of BENDER (1968) who suggested simultaneous deposition with Lake Lisan deposits. The transition between the deposits of the Gomorra-Amora Formation and those of the Samra Lake, based on a U/Th age determination occurred approximately 167000 years ago (WALDMANN et al., 2009) in the south of the Lisan Peninsula. The Samra deposits were determined to be about 20 m thick and Lake Samra had covered the Dead Sea basin until 75.000 years ago. Lake levels were approximately 50–100 m higher than the mean level of the Holocene Dead Sea and significantly lower than those of Lake Lisan that had a long lasting high stand at 170 m below sea level and higher than the present day Dead Sea, of less than 400 m below sea level (WALDMANN et al., 2009). Lake levels changed during existence of Lake Samra between 380 and 310 m below sea level with shifts up and down apparently correlated with the climate and global sea level rises. It was as low as 380 below sea level before begin of the history of Lake Lisan at 75.000 years ago.

18 Lake Lisan

The Lisan Formation is 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 and the lake existed approximately until 11 thousand years ago (NEEF & EMERY, 1967; NEEF & HALL, 1976; BEGIN et al., 1974). The Bakura River ended in Lake Samra Lake and its deposits were flooded when much fresh water entered Lake Samra and transformed it into Lake Lisan. This lake covered the whole Jordan Valley floor from the southern margin of Lake Tiberias to about 40 km south of the Dead Sea (KOLODNY et al., 2004). The alluvial deposits of the Bakura River were slowly inundated by the salty water of rising Lake Lisan as can be recognized quite well on several localities along the road in the Zor at the base of the Katar at the eastern side of the road runs parallel to the main road from Masharia to the north. Transition from the fluvial sands of Bakura River to Lisan deposits document that the waters of the lake came slowly. Alluvial flats became swampy at first with much organic material entering the sand. As soon as the salty lake flooded the soil the type of deposits changed to laminar and uninterrupted bedding. Composition of lake deposits reflected moist and cool winter and dry and warm summer deposition. Mud was washed into the lake during the moist periods and silt and sand was blown in at dry and windy periods.

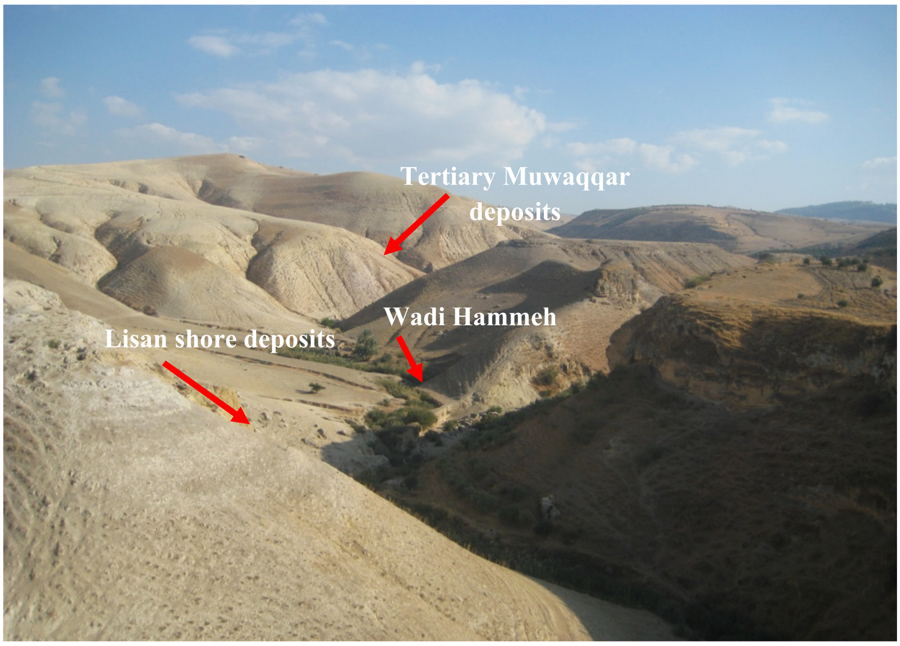


Fig. 29: View upstream into Wadi Hammeh with the ancient valley filling and central gravel bed eroded out to form an isolated mound in the end of the median ridge. The valley floor at Lisan time is the flat plain at the right side of the picture. Tertiary Muwaqqar sequence appears on the side and upstream in Wadi Hammeh, (in the Jordan Valley at Pella near Abu Thablah hot spring). The left arrow points at the layer with intraclasts, the upper arrow points at the Maastrichtian–Eocene Muwaqqar Formation, and the top flat of the hill is formed by the original valley fill at Lisan time (it lies in the upper middle of the aerial view).

At periods with relatively low lake levels the land sill at Wadi Malich (Marma Feiyad) (near and west of Al Qarn) divided the former single continuous lake, and separated it into two lakes (Bartov et al., 2002: Kolodny et al., 2004). When the Al Qarn sill was flooded; water flowed from the northern into southern Lisan Lake. The sill is exposed in Wadi Al-Qarn (Bandel & Shinaq, 2003; Bandel & Salameh: 2013, Fig. 112) with deformed Oligocene–Miocene deposits which underlie the Lisan deposits with a hiatus.
Between the towns of Shuna and Waqqas the former beach of Lake Lisan is locally preserved as beach rock that has developed close to former creeks which entered the Lake (Fig. 34). Here shells of *Melanopsis* are washed together by the waves of the lake (Bandel & Salameh, 2013: Fig. 118). These gastropods had lived in the fresh water of the creek that entered the lake but not in the salty water of the lake proper.
In Wadi Hammeh about 30 km S of Lake Tiberias Macumber & Head (1991) and Macumber (2008) noted that the ancestral valley was partially filled with 60 m of fluvial and swamp sediments including pebble bands and conglomerates and beds of clays and silts. The ancient shore near the confluence of former Wadi Hammeh into Lisan Lake is well exposed at the northern margin of that valley. Here deposits consist of sherds of dried mud forming layers of inter-clasts, sands resembling oolites, and minute pisolites, that developed around fresh water springs which provided the environment for growth of reeds and other vegetation. That formed the nucleus for calcification and formation of travertine. Smaller particles of carbonates were washed from the spring area to the beach of the lake and here were sorted according to size by its waves and by coastal currents produced during windy periods. Thus deposits resembling "oolites" have formed from soil-pisolites as well as from spring deposits.

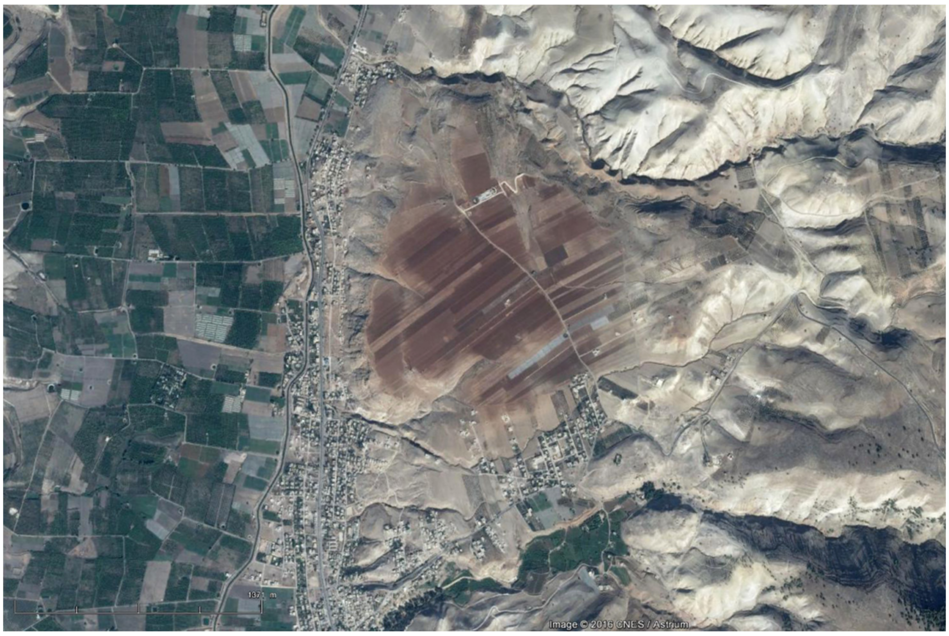


Fig. 30: The gravel fan between Wadi el Hammeh (North) (shown in Fig. 29) and the archaeological site of Pella (South) and the town of Masharia (West) formed when Lake Lisan was filled with water and its beach lay in the position of the road. The fan consists of gravel and has a margin of travertine rocks of which parts are also exposed on the western side of the road. The fertile fields on the top of the fan provided agricultural land for ancient Pella.

The water level of Lake Lisan fluctuated repeatedly (Bartov et al., 2002). Such changes in the position of the shore have been imprinted in the sediment on the northern slope of Wadi Hammeh (Fig. 33). Here travertine material of a former spring periodically mineralized and solidified sediment of the slope (Figs. 31 & 32). When sea level dropped a new shore line developed and its deposits were cemented by mineral water. During low stands erosion and cemented sediment blocks became instable and fell or slid down the slope when undercut by erosion, just to be subsequently covered again with new sediment. The cementation of loose valley fills and their becoming uncovered by renewed erosion occurred several times. The result is a very complex mix of generations of former valley slopes and gravel channels that had been successively consolidated by the calcareous deposits of the springs (Fig. 33). The last pebble channels which formed next to the travertine mass are still found undisturbed in place. They have been eroded when Lake Lisan finally withdrew from the area and relatively rapidly concentrated to form the Dead Sea.
Fossilized stems and roots of the reed *Phragmites* and remnants of other grasses and bushes such as *Tamarix* are common in the travertine present on the edges of the valley (Fig. 32). Shells of the abundant *Melanopsis* were used for age determination by radio-carbon analysis. Accordingly they formed about 15.000 to 30.000 years ago

(MACUMBER & HEAD, 1991). This agrees more or less with reconstructions of sea levels of Lake Lisan provided for example by BARTOV et al. (2002). A travertine bed (calcareous spring tufa) had formed during the existence of Lisan Lake and is exposed south of Masharia documenting that fresh water emerged here for some time.

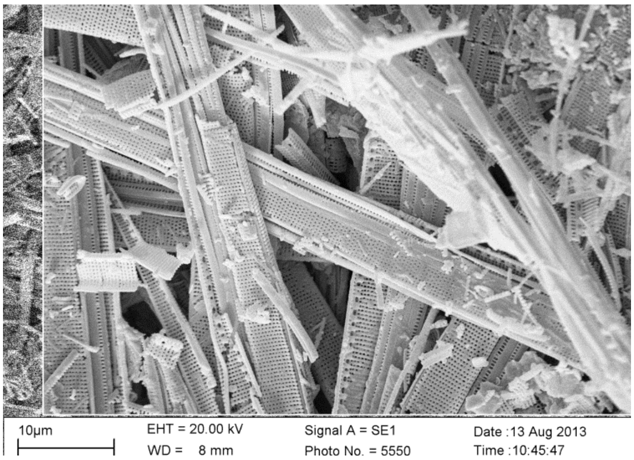
Figs. 31 (left) & 32 (right): Soft marl sediment of Lake Lisan shore consisting of mud with clasts and sand of oolitic fabric (North-western slope of Wadi Hammeh), coming from travertine debris at the upstream end of the travertine cliff (Northern slope of Wadi Hammeh near Pella, Jordan Valley). The spring water coated twigs and reeds, as well as shells and consolidated this to form a travertine.

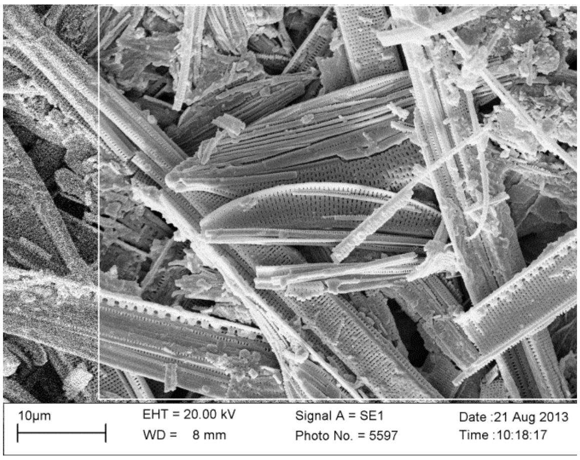
Fig. 33: Left – Wadi Hammeh northern slope with tufa of the spring above and slope deposits below. Right – Fig. 34: beach deposit of a smaller creek that entered Lake Lisan north of Waqqas below the bush and the inclined structures below have been produced by goats. The highest level of Lake Lisan lies just below the former spring in the slope (Fig. 33) and at the end of the small wadi (Fig. 34).

A travertine bed (calcareous spring tufa) had formed before the existence of Lisan Lake and is exposed south of Masharia documenting that a fresh water spring existed in that place for some time. The spring thus had its discharge above the Bakura River on its eastern margin of the Jordan Valley, before this area was flooded by the rising Lisan Lake. A travertine bed (calcareous spring tufa) had formed before the existence of Lisan Lake and is exposed south of Masharia documenting that a fresh water spring existed in that place for some time. The spring thus had its discharge above the Bakura River on its eastern margin of the Jordan Valley, before this area was flooded by the rising Lisan Lake.

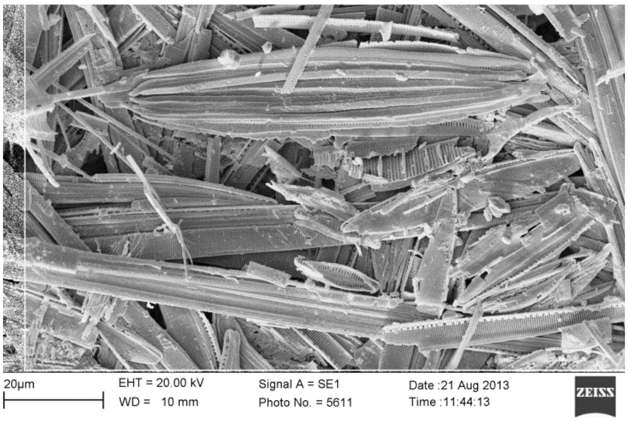
Northern Lake deposits

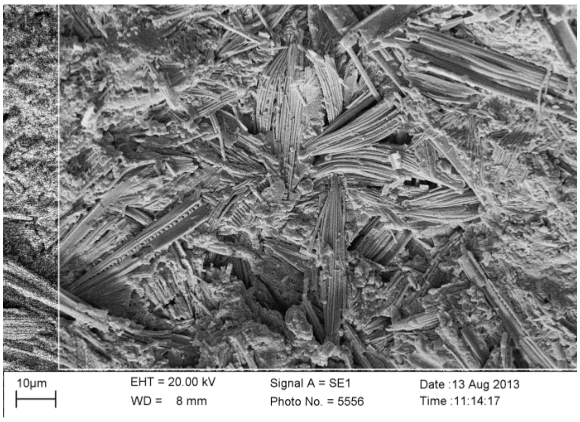
In the central Jordan Valley, for example near the slope to the Zor west of Al Qarn Ridge, some of the characteristic paper-like sediment can be composed predominantly of diatoms. Among them *Nitzschia* has usually straight and needle-like frustules (ROUND et al., 1990). A *Rhodopalodia gibberula* eco-stratigraphical zone as noted by MEISTER (1968) has the diatom *Rhodopalodia* with solitary cells and linear lancet like frustules. When living they may contain endo-symbiontic cyanophytes. Their dominant presences in distinct thin layers of the finely bedded Lisan diatomites reflect annual changes in the salinity of this ancient lake.



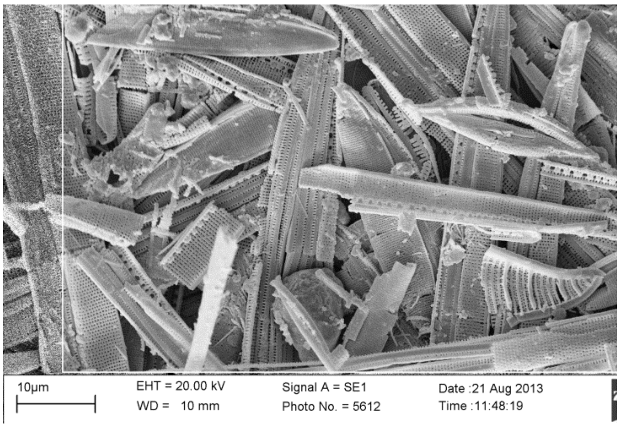


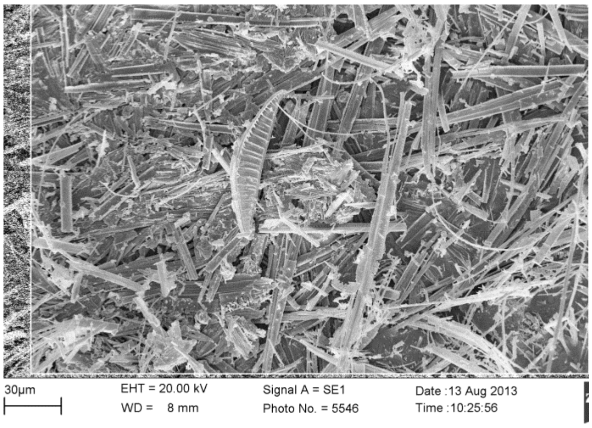
Figs. 35 (left) & 36 (right): *Nitzschia* sp. from Lisan beds, west of the Al Qarn bridge, and flattened *Rhodopalodia* together with a few fine sand grains from Lisan Formation, west of Al Qarn bridge.





Figs. 37 (left) & 38 (right): Diatomite from the beds of Lake Lisan near and west of Al Qarn ridge as exposed at the upper edge of the slope to the Jordan River flats show *Rhodopalodia* sp.





Figs. 39 (left) & 40 (right): Mix of different species of diatoms and layer in which the diatoms were partly disintegrated.

The lower laminated series (Laminated Bed) are described as being usually mono-mineralic composed mainly of aragonite needles, frequently associated with diatom frustules (MEISTER, 1968; BEGIN et al., 1974). The dark lamina is composed mainly of calcite associated with clay.

The laminated diatomites studied from Lisan layers collected near Al-Qarn do not agree to that description, but are predominantly composed of diatoms (Figs. 35–40). This composition is understood when, as today, the summers were hot and dry causing chemical sediment deposition in the lake, and the winters were more humid causing rivers to discharge muddy fresh water into the lake which formed a fertile less salty surface layer that enabled the diatom to grow in large numbers in the phytoplankton. The characteristic paper-like sediment can locally be composed of almost pure diatomite. The euryhaline diatoms of the *Nitzschia vitrea* eco-stratigraphic zone are present, while the dark zones have more fresh water forms. *Nitzschia* has usually straight and needle-like frustules and the genus contains many different forms, which have been split into different genera by ROUND et al. (1990). A *Rhodopalodia* eco-stratigraphic zone contains with euryhaline species also rare freshwater forms (MEISTER, 1968). *Rhodopalodia* is a diatom with solitary cells and linear lanceolate frustules which may contain endosymbiontic cyanophytes that lives in freshwater or marine environment (KRAMMER, 1988). ROUND et al. (1990) described *Rhodopalodia* as based on *Rhodopalodia gibba* (EHRENBERG) O. MÜLLER, 1895. Frustules have differing shape either linear or elliptical. Valves are often shape like an orange segment. Fissures of the raphe that lies closer to the dorsal side are often connected to a dorsal margin that is raised on a keel.

Lake Lisan beaches

Former beaches of Lake Lisan are preserved in the Jordan Valley from North-Shuna to the slope of the Dead Sea at many places, with the beach deposits best developed at around -170 m below sea level. Lake Lisan existed between 63.000–15.000 years ago and experienced several periods of low lake levels and during these may have formed independent portions partly separated from each other (KAUFMAN et al., 1992; SCHRAMM et al., 2000). GHAZLEH & KEMPE, 2009) reconstructed Lake Lisan levels to have reached levels higher than -170 m and connected high and low stands with glacial fluctuations as they have been recognized in Europe. On the slope to the Dead Sea the retreat of Lake Lisan left behind terraces of engraved former beaches (BENDER, 1968; GHAZLEH & KEMPE, 2009; BANDEL & SALAMEH, 2013: Fig. 117).

Lisan Lake began its final retreat at about 15.000 years and according to BARTOV et al. (2002) Lake Lisan reached its highest level during 27.000–25.000 years ago. Lake low stand was reconstructed by MACHLUS et al. (2000) by correlating fan-delta and lake deposits in Perazim Valley, southwest of the Dead Sea. They found the minimum lake level to have occurred 47.000 years ago and that it remained low for 3.000–4.000 years. Next to ancient beaches often stromatolites grew in the water (BUCHBINDER, 1981). This water was salty and similar cyano-bacterial knolls of the shape just as these stromatolites still formed in the Dead Sea at places where a fresh water spring entered the water just below sea level and near the shore 50 years ago. Approximately 10.000 years ago the level of the lake dropped sharply to -400 m (STEIN, 2002; KOLODNY et al., 2005).

Figs. 41 (left) & 42 (right): The surface of a beach-rock the on the Lisan terrace near and south of the "Panorama Road" has cracked pattern due to its former exposure. Large blocks of travertine of approximately 2.5 m in height which formed near a spring above the beach tumbled down the slope onto the terrace onto the angular fragments of the beach rock and the gravel beach.

One terrace along the northern slope to the Dead Sea north of Zerka Ma'in and around 170 m below sea level is well developed and indicates the highest stand of Lake Lisan (Figs. 41–45). This uppermost terrace formed by Lisan Lake is a quite visible plane within slope along much of the highland toward the Rift and the Dead Sea. Commonly travertine deposits are related to the ancient beach and sometimes still have active springs nearby. Often large boulders of travertine formed at different times and different lake levels are still present on the slopes. The waves of the Lisan Lake here had not only carved the terrace but also had been active in assembling a sandy beach in which solid and massive beach rocks formed. That rock ledge is still in place of its origin and is partly composed of laminated, often cross laminated sands and of angular fractured particles of older, reworked beach rocks. Numerous stromatolites forming nodules and knolls lived in Lake Lisan at this place and are still present in their original place of growth just below the beach rock terrace and in the area of former shallow water. This large and well recognized terrace documents a long lasting high stand of Lake Lisan.

Fig. 43: View from the upper Lisan Beach terrace with beach rock - towards south with the main upper terrace well incised in the slope and present by flats in the slope between the deep ravines.

Figs. 44 (left) & 45 (right): Beach rock of Lake Lisan composed of cross-bedded beach sand from the locality south of the Panorama Road, and stromatolites as present below the former beach, still in the position as originally formed in the shallow water of the salty Lake Lisan.

The White Cliff Member of Lisan Formation

The Lisan Formation in the central Jordan Valley consists mainly of varved sediments which are capped by a conspicuous white cliff containing gypsum lamina and is overlain by the evaporate-free Damya Formation. The varves represent layers of sedimentation which differ regarding the yearly changes from dry hot summers and moist winters with muddy water entering the lake by rivers and creeks. BEGIN et al. (1974) had studied the lithology of the Lisan Formation west of River Jordan along its entire length and subdivided it into a lower laminated member and an upper White Cliff Member. This topmost part of the Lisan Formation consists of a conspicuous 5–7 m gypsum and aragonite. ABED & YAGAN (2000) attempted to determine the age of these deposits as they are exposed near Karama Dam site by using the rate of sedimentation, assuming that the varves or lamina of the Lisan Lake sediments are seasonal. Accordingly gypsum lamina was deposited in summer, while the aragonite lamina was deposited in winter (BENTOR & VROMAN, 1960; BENTOR, 1963). EL-ISA & MUSTAFA (1986) counted the lamina assuming that a little more than 1 mm represents a year and calculated that the bottom of the gypsum cliff formed at 23.000–22.000 years ago and that near Damya the White Cliff is approximately 23.000 to 15.000 years old.

Damya Formation- and the reduction of Lake Lisan

NIEMI (1997) suggested that Lake Lisan developed into a sabkha with stromatolites growing along its shore. The saline water of Lake Lisan had been drained and replaced by fresh-water when succeeding Damya Formation was deposited (YECHIELI et al., 1993; FRUMKIN, 1997). Damya Formation is shown on the NRA map just NW of Karama as 14 m of siltstone on top of Lisan deposits – supposedly also Lisan beach rock. The deposits of the white cliff of the shrunken Lake Lisan are overlain by Damya Formation (Fazael Formation of HOROWITZ, 1979). The Damya is several meters thick with clay, silt, sand, and some gravel with no evaporates. BEGIN et al., (1985) suggested that the Damya deposits formed when lake level was dropping at about 15.000 years ago. Damya sediments cover the deposition of the White Cliff Member and the formation is up to 14 m thick in vicinity of Damya in Jordan and has delivered fresh water ostracods (ABED & HELMDACH, 1981). According to ABED et al. (2004) Damya Formation formed in a fresh water lake that lay in the vicinity of the Ghor El-Katar area, and GHAZLEH & KEMPE (2009) noted these deposits near Al-Karama City, Jordan at -180 m above sea level and thus only 10 m below the level of the lake during most of its existence. LANDMANN et al. (2002) analyzed Damya sediment and confirmed the influence of fresh water during its deposition.

The soil noted to overly beach deposits of Lake Lisan near Karama dam-site can also be placed with Damya Formation, which here rests on sandy laminated layers and not on gypsum of the white cliff type, which is not developed here (Figs. 15 & 16).

Shrinking of Lake Lisan may have been speeded up due to the reduction of the catchment area from around 157.000 km^2 to about one fourth due the spread of basalt flows of the Jabal Arab-Druz blocking the drainage. Water coming from the east, after that, remained in the area of Azraq Oasis, Sirhan Basin, Damascus Oasis and others (SALAMEH & AL FARAJAT, 2006). These basins were since then filled with sediment. Thus Lake Lisan shrank rapidly in size from relatively high stand about 17.000 years ago to about the level of the Dead Sea 13.000 years ago.

At the outcrops near the dam site of Karama sandy laminated Lisan deposits are intercalated by beach deposits of reworked Ghor al Katar gravel beds (Figs. 17 & 18). The top of such beach gravel consists of silt-sand beds of the Damya Formation, which represents alluvial and soil deposits which formed when Lake Lisan had withdrawn to the south. When shrinking the salinity increased and thus gypsum was deposited further south of these beaches. Archaeological remains suggest that the region north of the salty lake was home to elephants, lions, hippopotami, rhinoceroses, leopards, boars, ibexes right after Lake Lisan began to shrink (MACUMBER, 2009).

19 The Recent History of the Dead Sea Level

The Dear Sea formed when Lake Lisan shrank in size due to evaporation, leaving beach terraces during this process, the uppermost with a locally broad beach platform is the “Oberterrasse” of PICARD (1932). The transition interval between 19.400 and 12.000 years of Lake Lisan changing into the Dead Sea is recorded by STEIN et al. (2010) and occurred from Pleistocene to Holocene. Lake Lisan began its retreat ~17,000–15,000 years ago (BEGIN et al., 1985), and reached its minimum stand ~13,000–12,000 years ago (STEIN, 2002). The terraces formed by sinking Lake Lisan are well developed on the slope above the southern extension of the Dead Sea south of Lisan Peninsula and BENDER (1968: Fig. 98) counted 28 such beach walls and they have also been described in detail by GHAZLEH & KEMPE (2009). From a section obtained from drilling in the deepest basin of the Dead Sea at approximately 723 meters below sea level sediment cores allowed to reconstruct the history of the Lake between the present day to approximately 200.000 years back (TORFSTEIN et al., 2013), with the chronology established by integration of U-Th ages of primary aragonite, $\delta^{18}O$ oxygen isotope stratigraphy and lithology of the encountered units. Accordingly between 17.400 and 16.000 years ago the lake level dropped from -260 m to -330 m, depositing a thick sequence of gypsum. Between 16.000 and 15.000 years ago the lake level shortly recovered but between 14.600 and 13.200 it dropped abruptly to below -465 m. Between approximately 13.000 and 11.000 years ago the lake level rose above -400 m and declined again at approximately 11.000–10.000 years ago depositing a thick sequence of salt. The changes in the climate were traced by NEUMANN et al. (2007) with the help of pollen and spores.

The shrinking of the Lisan Lake can have been the result of the reduction of the catchment area from around 157.000 km^2 to about one fourth of that area. Reason for that reduction is the spread of basalt flows of the Jabal Arab-Druz blocking the drainage. Water coming from the east, after that, remained in the area of Azraq Oasis, Sirhan Basin, Damascus Oasis and other basins (SALAMEH & AL FARAJAT, 2006). Thus Lake Lisan shrank rapidly in size to about the level of the Dead Sea 13.000 years ago.

20 Results and Discussion

After the regression of the Tethys Ocean from the northern African Plate a fracture developed, along which the Arabian plate detached from the Sinai sub plate. The African plate was thus split by the rift zone of which the Jordan Valley-Dead Sea Rift is a part. During the Oligocene the rift of the Jordan Valley was initiated and the Levantine side of the valley detached from its Arabian side, the floor of the rift valley began to sink and both sides moved against each other. The separation resulted in the formation of a Graben, the Jordan-Dead Sea Rift and displacement of the eastern side in regard to the western side by more than 100 km. A remnant of the Tethys Sea coming from the W, NW flooded part of the Northern Jordan Valley and marine sediments of Tayba Formation of Late Oligocene and Early Miocene age were deposited. During deposition of Tayba Formation the mid-Tertiary sea flooded the newly form Jordan Rift depression leaving remains of a micro- and macro fauna with Tethys affinities. A characteristic Mediterranean fauna began to develop only later. Along the eastern margin of the northern part of the Jordan rift that sea had its shore now exposed between the towns of North Shuna and Waqqas. In the central part of the sinking graben shallow water sediment was deposited with gravel beds intercalated, exposed further south of Waqqas next to the Al Qarn ridge near the town of Abu Habil. The fluvial conglomerates and sands intercalated with deposits of marine lagoon have come predominantly from the east as their composition documents. Gravel can be recognized to belong to eroded Paleogene and Cretaceous rocks as had been deposited on the Jordanian Tethys shelf east of the Rift. While the shore was settled with rich marine life, the depression of the rift graben to the south filled with shallow water deposits of more lagoon character with inter-bedded calcareous sand partly composed of the shells of pelagic organisms such as foraminifera, as present in Wadi al Qarn.
The sea gulf turned saline within the early Miocene and connections to the open sea was closed. The Rift floor continued to sink until it may have been well below sea level.
During the Messinian Stage in the late Miocene the Mediterranean basin had become detached from access to the Tethys-Pacific Sea and when its connection to the Atlantic Ocean was shut, the sea dried out. Thus to the West of the Jordan Rift and west of the slope towards the Mediterranean Sea the deep-lying Levantine salt lake formed, that, according to references was up to 3 km deep. In our reconstruction the Jordan Rift connected to the Levantine basin with a river bed formed by a Paleo-Yarmouk River that collected the runoff from the Arabian Sirhan depression. This river with its catchment in the east continued across the Rift Valley carving out a canyon- the hypothetical Beisan Canyon connecting the Rift depression to the Mediterranean Basin. Before the Mediterranean Sea filled again with sea water coming from the Atlantic Ocean, fresh water from the North entered the Mediterranean Basin bringing with it the Lago Mare fauna. These animals may have entered the Jordan Rift via that Beisan Canyon following ancient Yarmouk River. By that way the characteristic fresh water animals derived from the region of the Paratethys in the North entered the Rift and the connected rivers and creeks. Its characteristic faunal representatives still compose the Jordanian fauna of the fresh water by gastropods such as *Theodoxus*, *Melanopsis* and *Melanoides*. The same Beisan Canyon subsequently could have given access to sea water when the Mediterranean Basin filled again during the Zanclean flood in the transition from Miocene to Pliocene. Former salt deposits in the rift that may have been present from the early Miocene could have been flushed out by way of the canyon before that time or have locally been preserved in the Rift Valley. The sea water which entered the rift valley during the Zanclean flood was assembled in the northern depression of the Lake Tiberias region and the larger southern depression of the Dead Sea to Karama area. Water coming into the Rift from the Levantine Basin may have been derived from the Levantine salt lake there and thus at least in part have been more salty than normal sea water. North of the Dead Sea salt deposits were subsequently covered by terrestrial deposits. These formed in great masses due to the rising of the margin of the Arabian plate. Rivers dumped erosion materials into the rift which sank according to drill site and geophysical data for 6–14 km, most deeply in the region of the southern Dead Sea.
The Northern salt lakes evaporated and the salt was covered and sealed by alluvial deposits. Here on the valley floor the ponds, river arms and lakes were the living environment of mollusks with character of such from the Paratethys and related to those that lived in Pliocene lakes of Rhodes and Kos. Al Qarn Formation was laid down directly overlying the Oligocene–Miocene Tayba Formation with an angular unconformity. Gravel beds of the Al Qarn Formation hold layers which are composed of oncoids that had grown in the soil which was eroded from the slopes. The deposits of Al Qarn Formation were subsequently deformed due to the further movements of the bottom of the rift valley. A similar deformation with westward dip took hold of the Ghor El-Katar Formation representing alluvial gravels separated from each other by soil horizons. These beds were subsequently tilted to

the west affected by the Rift tectonics and covered by some basalt, perhaps of nearly equivalent age to the Aramshi basalt plug.

When the region began to be uplifted a new Jordan Valley plain evolved on which a local lake deposited Aramshi Formation with a similar fauna to that of the older Al Qarn Formation. It rests on a local volcanic deposit and may have been connected to a warm spring. The flat plain of the Jordan Valley which held the Lake and springs of Aramshi Formation was subsequently eroded and later Bakura River cut into the valley floor and eroded a valley of similar dimension as the valley excavated by the modern Jordan. The Al-Qarn sill probably evolved together with the Marma Feiyad after the Tertiary sea and its deposits and even after the time of deposition of Al Qarn Formation and before that of Aramshi and definitely before Bakura River caved its bed into the swell. Movements after deposition of Al Qarn Formation produced the stronger dip toward the west resembling that of Ghor al Katar Formation. Aramshi Lake deposition was only much less deformed. The formation of the valley floor during Aramshi Lake spring may have been at the time when the highland was rising. It may have acted as divide of a less salty northern Lake Lisan and a southern more Dead Sea-like Lake Lisan.

The molluscs which lived in Bakura River are very similar to those still living in Jordan. Sedom-Amora salt was a Messinian–Pliocene deposition and Samra salt was laid down at Pleistocene. The transition from the valley floor as preserved with Aramshi Lake to the valley of Bakura River represents the most likely time of rapid rising of the margins of the Rift. A series of fluvial deposits formed over extended areas west of Irbed to the Jordan Valley and fill many river channels. In the northern Lower Jordan Valley Bakura Formation may be equivalent to some of these alluvial deposits. The source of these sediments is the Jordan highland and eroding and transporting rivers had their catchment here. Some came from the extension of Wadi Sirhan before that drainage basin was blocked by Huran and Harrat esh Sham basalt flows. These volcanic materials blocked water from reaching the Jordan Valley area. Before the eruption of Huran and Harrat esh Sham basalts, Wadi Sirhan catchment of about 120 km^2 used to discharge into the Jordan Valley through the area extending from the Yarmouk River in the north to Wadi Yabis in the south. This huge catchment was able to provide all the sediments of the Bakura Formation.

The fluvial Bakura Formation was subsequently covered by the rising level of the Samra Lake changing into Lisan Lake that way. That salty lake was less salty in the north than in the south, and the dividing zone between both parts of the lake was the Wadi al Malih- Wadi al Qarn narrow. In the northern lake plankton of diatoms changed in composition with winter and summer, reflecting differences in the amount of inflow of fresh water. The former shore of the lake is locally preserved including its beach deposits. The fluctuations of lake level are documented to the north of Pella. After the Lisan Lake shrank into the Dead Sea the Jordan has cut its ventral valley of the Zor into the deposits of Lisan Lake bottom, the Lisan Formation. Deposition in the Zor allows distinguishing a northern part of the rift with little vertical movement, a central portion with erosion and a southern portion with local evidence of rising salt dome, one close to Karama dam site

Bakura River was only partly ancestor of the Jordan River since the Hula Basin at the time of Bakura Formation deposition was not connected to Tiberias Basin let alone to the Dead Sea. A catchment area of a few hundred square km served as source of the sediments to provide all the gravels and sand of the Formation especially.

The river terraces near Awsara may be correlated to wadi Sirhan waters and were deposited before the basaltic eruptions of Huran and Harrat esh Sham blocked the drainage of Damascus, Hammad, and Sirhan basins from reaching the Jordan Valley area. Samra and Lisan Lakes may have received their water also from the basalt eruption catchment area of around 157.000 km^2 of which around 120.000 km^2 are formed by the drainage basins of Damascus, Hammad and Sirhan. The upward movement of the Jordanian highlands also lowered the amount of water which reached the Jordan Valley area and may have resulted in the shrinkage of the Lisan Lake from about 3.000 km^2 in area to form the Dead Sea of the pre-development era which before the 60s of the last century occupied of 950 km^2.

A salt dome below the Karama area was rising during existence of Lake Lisan and pushed up the bottom to form hills rising from the valley floor and even above the surface of Lake Lisan. Its presence results in salty springs which still issue into the lake (ALHEJOI et al., 2015). The gravel beaches present in Lisan deposits from the salt dome hills near the Ghor al Katar deposits document movement of salt domes during the time of Lake Lisan. The salt within the deposits of the Rift may in part have been deposited during the Miocene but these early deposits can also have been flushed out through Beisan Canyon before the arrival of new salt water by way of that canyon which provided the channel for the Zanklean flood to reach the rift.

Lake Lisan deposits of the south have a lower portion with aragonite and the upper member with gypsum layers of the White Wall and of the north with laminated silt with aragonite and diatomite. The broad uppermost Lake Lisan terrace near the road to Madaba can be correlated with data from Wadi Hammeh and beach deposits north of Waqqas and they together document an extended period of water level of Lake Lisan at around -170 m. Dayma Formation that lies up to -180 m near Karama – formed when Lake Lisan had decreased in size to the position of its northern shore south of the mouth of Zerka river. Shrinking of the lake resulted in gypsum deposition when the lake had found a position south of Damya and only in the southern part when salinity conditions approached those of of the Dead Sea.

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