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TECTONIC AND NON-TECTONIC MESO-STRUCTURES IN THE LISAN FORMATION AND EQUIVALENT RECENT SEDIMENTS OF THE JORDAN RIFT VALLEY-CHARACTERIZATION AND FORMATION MECHANISMS

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Abstract: In this study, the structural elements portrayed in the recent sediments of the Dead Sea, which became exposed at its shores due to the drop in its level are described, and the mechanisms leading to their formation are elaborated. These structures include Plumes and density inversions, subaquatic gliding, seismites, undulations and wavy structures, flexures, and overpressure structures. The formation of these structures is found to be the result of different triggering factors such as Earthquakes, tectonic activity, instability of slopes, density inversion, pore fluids overpressure resulting from gas production by biochemical processes within the sediments (sulfur bacteria reduction of sulfates and oxidation of organic matter (petroleum residues)), submarine groundwater discharge, and volume changes associated with the transformation of gypsum to basinite and anhydrite, and the reversal of that transformation. Each of these triggering factors can produce more than one type of structure, depending on the prevailing composition of the sediments, its layering attitudes, grain-size distribution, porosities, and differential pressure situations within the sediment packages. The main finding of the study is the clarification of the role of gas production within the sediments as a result of sulfur bacteria activity and of the volume change processes associated with the transformation of gypsum to anhydrite and the reversal of that transformation in the formation of the mesostructures of the Dead Sea sediments.

Keywords: Lisan Formation, seismites, plumes, density inversions, undulations, Jordan Rift Valley

1. INTRODUCTION

In the Lisan Formation and age-equivalent sediments of the Jordan Rift Valley of the Late Pleistocene age, a variety of mesostructures are found, which deserve special attention to classify their types and clarify the forces and mechanism behind their formation.

These structures include flexuring, faulting, meso-folding, plume formation, seismites, subaquatic gliding, and others.

The Lisan Formation and its age-equivalent sediments were deposited during the lifetime of the ancestor sea of the Dead Sea, namely, Lake Lisan, in the period of around 80.000 to around 12.000 years ago (Niemi et al., 1997; Horowitz, 1979, Begin et al., 1974; Bender, 1968; Neev & Emery, 1967) (Figure 1A). The Lake water level at that time fluctuated between about 160 m bsl (Below Sea Level) down to about 400 m bsl. The Lisan Lake sediments are mainly composed of coarse clastics of clays, marls, chalks, and silts, in addition to gypsum, and very limited thin halide layers or patches in the form of varved bedded layers (Abu Al-Haj & Salameh, 2020; Khoury, 2019, Abdel-Fattah & Khoury, 2001). In the upper part of the Lisan Formation, several gypsum layers of a few cm in thickness are found showing a wavy structure of up to 5cm amplitude and up to 25 cm wavelength.

The Lisan Formation was deposited in Lake Lisan proper and at its margins it interfingered with alluvial, lagoonal, and sabkha sediments (Bender, 1968). In all these sediments a variety of meso-structural deformation phenomena is present portraying the tectonic and non-tectonic activities, which took place in the Jordan Rift Valley area and its surroundings during and after the deposition of Lake Lisan sediments.

The Lisan sediments were studied on their geology, evolution, mineral composition, fossil content, and many other aspects by Blanckenhorn

(1914), Picard (1965), Bentor & Vroman (1960), Bender (1968), Neev & Emery (1967), Horowitz (1979), Niemi et al., (1997), Bandel & Salameh (2013), Abu- Al-Haj & Salameh (2020), Salameh et al., (2019) and by many others. Meso-structures in these sediments were described in some of the above-mentioned works and other studies. Similar structures occur in older rocks in Jordan (Alhejoj et al., 2018; Alhejoj & Salameh, 2023) and the present work related to structures in the recent Lisan Formation rocks, reflects the mechanisms used to explain the older structures.

This study tries to classify the existing structures according to their types and relate their formation to forces and mechanisms, which had led to their development.

1.1. Geological and tectonic settings

The Jordan Rift area is a depression in the Earth's Crust formed by down faulting along its N-S trending direction and is considered a pull-apart basin, with uplifts of its Shoulder Mountains on both sides, east and west (Figure 1B). Although the depression formed in Precambrian time as a weak zone in the Earth's Crust (Bender, 1968), it has become very active since the Middle Tertiary. Throughout its recent geo-evolution, the depression has functioned as a base level for the surrounding surface and groundwater sources and their sediment loads, which are deposited in successive lakes. The last of them called Lisan Lake from around 80.000 to around 12.500 yrs. (Bender, 1968; Neev & Emery, 1967; Begin et al., 1974; Horowitz, 1979; Niemi et al., 1997). The deposits in the depression are generally composed of clastic materials originating from the surrounding areas. In certain stages of the Rift's evolution, chemical deposits were also laid down. The interplay of graben tectonics and sedimentation has led to different sedimentation phases and facies. The Lisan Formation contains both chemical and detrital deposits, which change along that lake and across it.

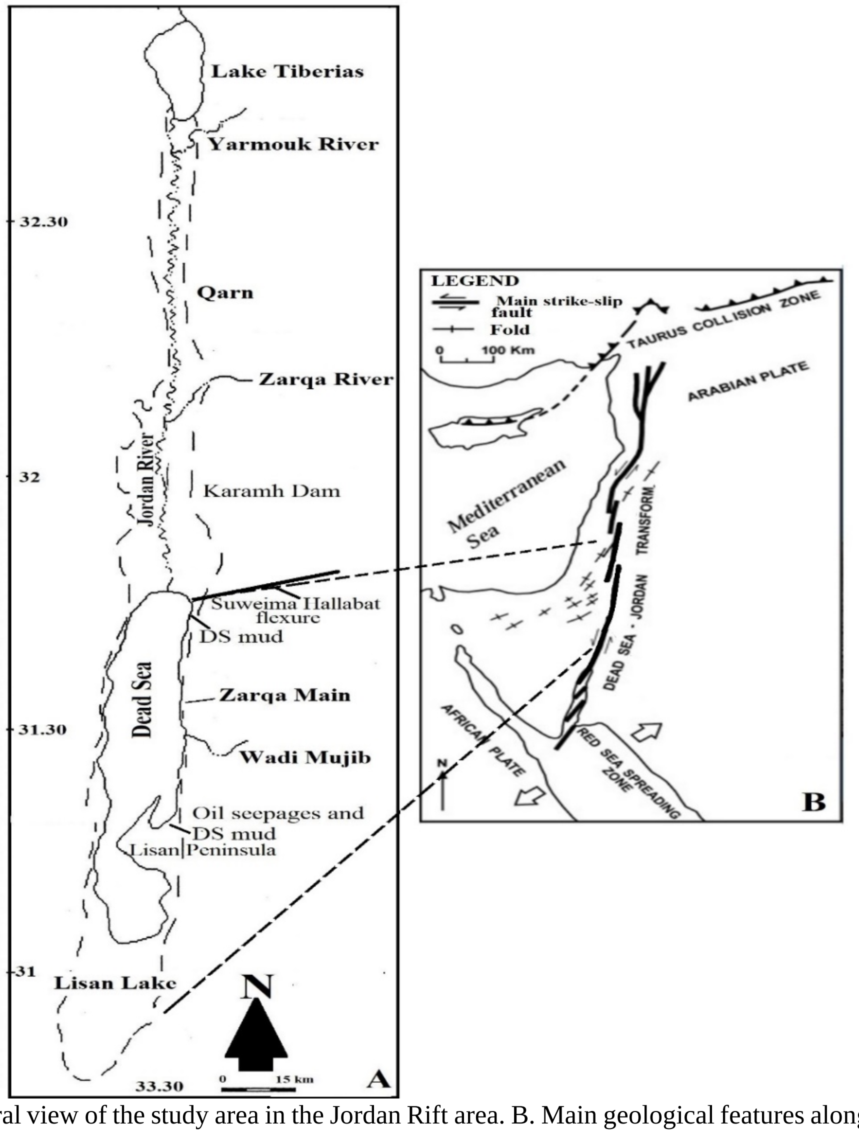

Figure 1. A. General view of the study area in the Jordan Rift area. B. Main geological features along the Jordan Rift area.

1.2. Methodology

This study is bases on documenting, fieldwork (including collection of samples), mapping, and laboratory analyses using mineralogical, geochemical, geo-engineering, structural, and hydrogeological techniques.

1.3. Meso-structural elements in the Lisan Marl Formation and equivalent sediments and the mechanisms leading to their formation

Fieldwork in the Jordan Valley area, where the Lisan Formation and its age-equivalents fine-grained sediments were deposited (Figure 1), allowed recognition of the following variety of mesostructures that deserve description and definition of the mechanisms leading to their formation whether tectonic or non-tectonic mechanisms:

- Undulation and wavy structures
- Plumes and Density Inversions
- Subaquatic gliding
- Flexures
- Seismites
- Structures Formed by Over-pressurized Fluids

During the fieldwork and also from documented existing literature, the following observations are found remarkable and seem to deserve due consideration in the course of the current study:

1. H_2S smell along the eastern shore of the DS, even in areas with no obvious discharges of thermal mineralized water containing H_2S
2. Residues of organic matter (bitumen) within the matrix of fine-grained sediments and as secondary deposits on joint surfaces (Wadi Numeira, Wadi Isal, Suweima Mujib, etc.)
3. Deposition of iron and manganese oxides from water seepages along the eastern shore of the DS
4. Sulfur concretions within the Lisan Formation and on rock surfaces

In the following, these observations will be related to the recognized mesostructures and the interplay between both of them.

2. UNDULATIONS (WAVY STRUCTURES)

A wavy meso-structure gas has been observed in the gypsum layers of the Lisan Formation, especially in the Lisan Peninsula area (Figure 2A). The Lisan rocks there are composed of alternating marl, chalk, and gypsum layers (of up to 5 cm in thickness), in addition to halite residues. Only the gypsum layers show the wavy structure, whereas, the overlying and underlying rocks show attenuating weak wavy structures seemingly accompanying or as a reaction to the wavering of the gypsum layers, but that weak wavering dies out very rapidly in a vertical direction (Figure 2B, C). Anhydrite, although expected, has not been observed. It might have converted to gypsum by hydration (Abu Al Haj, 2015; Salameh et al., 2019).

The mechanism of the formation of the wavy structure in the gypsum layers indicates that its origin is non-tectonic and is a result of the gypsum layer texture. Under the climatic conditions prevailing nowadays or which prevailed during the deposition of the Lisan Formation only gypsum could have been deposited from the water and not anhydrite, which requires other temperature, pressure, moisture, and ionic strength conditions (Bender 1968; Horowitz 1979).

Precipitation of gypsum, $CaSO_4.2H_2O$ from the salty Lisan Lake water could only have taken place after the water had reached the stage of saturation or oversaturation with respect to gypsum stage. The precipitation of gypsum results in disturbances in the common ion effect of the water solution and in reducing the ionic strength of the remaining water of Lisan Lake. Due to that, the other salts' concentrations in the remaining water become unstable, especially halides in the very salty water, which become oversaturated and start to precipitate immediately following the precipitation of gypsum (Cameron, 1901; Bock, 1961; Blount & Dickson, 1973). At this stage, the precipitation of halides enhances, in turn, the precipitation of gypsum due to the additional reduction of the solute ionic strength, and upon that gypsum and halides co-precipitate.

Upon compaction by continuous sedimentation, water is pressed out of the crystalline matrix, and at a certain load, the unconsolidated rock pores become overfilled with halides and gypsum brines. At this stage, the hygroscopic tension of halides starts to extract H_2O from the gypsum mini crystals ($CaSO_4.2H_2O$) and to transfer them into basinite ($CaSO_4.1/2H_2O$). This process continues until all gypsum transfers into basinite and may be also into anhydrite, which have the same orthorhombic crystal system but with far smaller specific volume or higher density of basinite and anhydrite (Gypsum density 2.2-2.3 g/cm3 gradually increasing with the loss of structural water to 2.98 g/cm3 for anhydrite), (Voigt & Freyer, 2023). Under the pressure of the overlying sediments, the reduction in volume from gypsum to basinite and anhydrite takes place in a horizontal direction within the rock matrix because of the strong overburden load of the overlying sediments and the semi-solid nature of all these salts. This process continues as long as the solute ionic

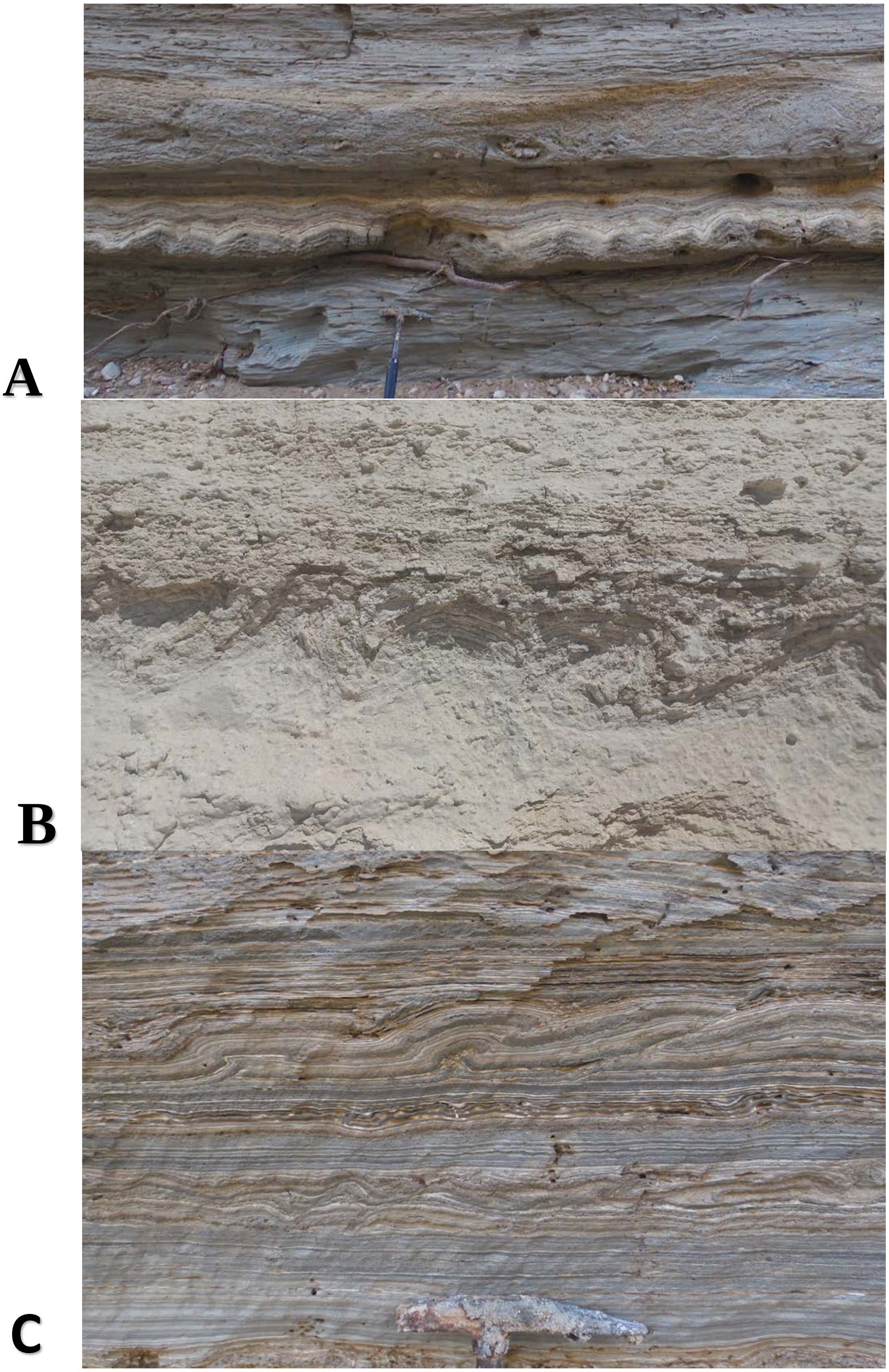

Figure 2. The wavy structure of the gypsum layers in the Lisan Formation is caused by the dehydration of gypsum to basinite or anhydrite accompanied by a reduction in volume followed by rehydration of basinite and anhydrite to form gypsum accompanied by increases in volume. That expressed itself in the wavy structure (A, B) due to restricted horizontal expansion potential resulting from the enormous frictions with overlying and underlying beds. Due to special problems the wavy structures developed into undulations overriding each other (C).

strength is in disequilibrium with the dissolved/precipitated minerals and as long as the sediments are deficient in their water contents. It continues until all gypsum transfers into basinite and anhydrite. The latter then lithifies with time.

When the lithified sediments receive new low salinity water (e.g. new flooding) the deposited halides dissolve and leave the rock matrix gradually and the new water rehydrates the basinite and anhydrite to gypsum again, a process accompanied by volume increase of the transferred basinite and anhydrite to gypsum of up to around 60%. That increase in volume takes place in a vertical direction due to restricted horizontal expansion potentials (Extended layers), thus producing the wavy fractured structures in the gypsum layers of the Lisan Lake sediments. Hence, the wavy structure of the gypsum layers in the Lisan Lake sediments is of non-tectonic origin and is related to the transformation of gypsum to anhydrite and the reversal of that transformation accompanied by volume change and its special complications, which natural solution seems to be expressed in the formation of the wavy fractured structure of the gypsum layers.

3. PLUMES AND DENSITY INVERSIONS

The Lisan sediments, especially those deposited in the near-shore areas contain organic matter or have been receiving organic matter from the groundwater originating from the highland aquifer and joining the Lisan Lake and its successor, the Dead Sea (Abu-Al-Haj, 2015, Khoury, 2019; Abu Ajamieh et al., 1988)

The Dead Sea Mud at the NE corner of the Dead Sea consists of alternations of thin to very thin, dark gray, black, and white beds and laminations with thicknesses of 1 and 30m. The black mud particle sizes of tested samples range from 0.98 to 3.9 μm and the mud is very well sorted with a standard deviation of less than 0.09 (Abu Al-Haj, 2015) this entails the mud has a very low permeability.

The analyses of the mineral content of the mud show that the mud contains quartz followed in quantity by calcite and halite as major components. In addition, kaolinite, smectite, montmorillonite, illite, hematite and pyrite were detected. Gibbsite and siderite were also detected in some samples. Anhydrite, although expected, has not been observed. It might have converted to gypsum by hydration (Abu Al-Haj & Salameh, 2020; Salameh et al., 2019).

The only very small amounts of gypsum found in the sediments and the presence of FeS_2 and H_2S smell indicate the continuing reduction of sulfate and oxidation of organic matter by the activity of sulfur bacteria (Khoury, 2002).

Seepages of asphalt, oil, and gas in the surroundings of the Dead Sea are mentioned by many researchers, such as Gardosh et al., (1997), Abu Ajamieh et al., (1988), Neev & Emery, (1967), Bender (1968), Bentor & Vroman, (1960) among others.

Along the eastern shore of the DS, one can smell H_2S in the air, not only in areas surrounding thermal water discharges loaded with H_2S but also along areas on the shore with no obvious thermal water discharges. The DS mud, which has become exposed due to the retreat of the DS smells strongly after H_2S and iron and manganese oxides precipitate from the water seeping from the mud. The production of H_2S is the result of sulfur bacteria reduction of sulfates (SO_{4-2}) supplemented by anaerobic organic natter biodegradation. The reduction of sulfates within the Lisan Lake and its equivalent sediments near the shores seems to take place according to the following equation (Domenico & Schwartz, 1990):

$CH_2O + SO_4^{-2} + 1/2H^+ +1/2\,(OH)^- \square\ 1/2HS^-(g) + H_2O + CO_2(g)$

Where: CH_2O expresses the organic matter, which can be composed of petroleum or earth gas leakages into the Dead Sea sediments directly or through the surroundings' groundwater seepages into the Dead Sea. The organic matter could also be composed of heavier organic hydrocarbons such as oil (Pentane: C_5H_{12}, Octane: C_8H_{18}) and asphalt molecules, which produce more CO_2 and HS^- (H_2S) gases. H^+ and $(OH)^-$ are dissociated H_2O in an acidic environment e.g. when HS^- reaches the water.

The input compounds in the above reaction are composed of organic matter, SO_4, and H_2O dissolved in the pore water and hence they occupy very small volumes in the rock matrix. Whereas, most of the output compounds consist of gases HS^- and CO_2, and have very large volumes hence their production is accompanied by high fluid pressure in the pores of the sediments resulting in the instability of the sediment packages. When the over-pressurized fluids start to leave the semi-consolidated rock packages, they disturb the layering structure of the sediments and form flow plumes, density inversion structures, and liquefaction features.

One mole of CH_2O dissolved in water plus one mole of SO_4^{-2} dissolved in water (also occupying very small negligible volumes) produce ½ mole (liter) of HS^- gas and 1 mole (liter) of CO_2 gas.

This means that the reaction, which generally takes place as a result of sulfur bacteria activity, produces 1½ liters of gases within the sediments, which causes the fluid over-pressure in the sediments. In addition, the compaction of the sediments is accompanied by the expulsion of pore water, which adds to the instability of sediment packages. The expulsion of the produced fluids results in a high variety of flow structures expressed in plume structures (Figure 3 and 4).

4. SUBAQUATIC GLIDING

Fine-grained sediments, mud, marl, clay, silt, and sand, and chemical sediments such as gypsum and carbonates deposited in near-shore areas are generally deposited on slopes inclined towards sea bottoms (Figure 5). The sediments are laid down as suspensions or accumulations of very loose sediments with high porosity and water content (Pettijohn, 1975). Gradually, with additional sediments topping the older ones, and with time such sediments start to consolidate. But unless they are adequately consolidated, they remain labeled and exposed to gliding along their slope directions.

The triggering factors for gliding are instabilities due to:

Figure 3. Plume structure with pieces (white color) of semi-consolidated low-density chalk moving upwards in the dense heavy clay matrix (grey color) at the newly evacuated shore of the Dead Sea west of Sweima Village.

Figure 4. Water seepages at the recently evacuated shores of the Dead Sea (Wadi Al Abiad, South of Sweima)

Figure 5. Subaquatic gliding in the Lisan Formation at the NE shore of the Dead Sea (Wadi Sweima).

- Differential up and down movements within the slopes leading to instability and gliding
- Differential overburden loads in the different parts of the sediments
- Seismic agitation and liquefaction
- Differential pore pressures in the different parts of the sediments caused by digenesis and disintegration of chemicals (especially organics) leading to fluid overpressure. In addition, submarine groundwater seepages and springs may produce differential pressures in the sediment packages.

The Dead Sea area has been tectonically very active since the recent activation of the JRV structure after the retreat of the Tethys during the Oligocene. Tectonics (taphrogenic movements) resulting in the uplift of the JRV Shoulder Mountains created increasing slopes of the topographic configuration in the surroundings of the Dead Sea, which has led to changing depositional conditions in the Dead Sea, especially along its shores and produced instability in the unconsolidated layered sediments.

Most of these triggering factors produce liquefaction in unconsolidated or semi-consolidated sediments with high water contents. Figures 5 show subaquatic gliding in the recently exposed Dead Sea sediments.

5. FLEXURING STRUCTURE

At the NE edge of the Dead Sea reversely flexured Lisan sediments crop out striking ±700 ENE along the western extension of the major Suweima-Hallabat structure, the latter extends from the NE edge of the Dead Sea to the Hallabat area, around 70 km ENE of the Dead Sea, where the structure dies out. The structure starts at the NE edge of the DS as a vertical or even slightly reversed fault dipping 90-800 S with a down-thrown northern flank of about 500m throw. At around 15 km ENE of the DS, the structure develops into a vertical or even slightly reverse fault dipping S. In the eastern part of Amman City, it turns into a monoclinal fault with a downthrown northern flank, and in the Hallabat area, the structure dies out. Along this structure, vertical faulting, flexuring, and dextral strike movements are mapped (Wiesemann, 1969; Al-Tarawneh, 2014). At the NE edge of the DS the structure is covered by the Lisan Formation and the structure's continuous activity is observed on the deformation of the Pleistocene Lisan and equivalent sediments there (Figure 6).

Therefore, the mechanism behind the formation of such flexures and bending can be referred to as the still ongoing activities of older structures. Tectonic activity in the Jordan Rift Valley area seems to have been and still be depicted in the deposited sediments there.

6. SEISMITES STRUCTURE

Seismites in rock formations represent agitation of semi-consolidated sediments affected by strong vibrations of the ground triggered by earthquakes, huge landslides, major rock collapses in nearby areas, or meteoritic impacts (Alhejoj & Salameh, 2023). These same triggering factors cause generally fluidization (Liquefaction) in the semi-consolidated sediments, which leads to density inversion, slumping, subaquatic gliding, and other features.

Worth mentioning here is that, in most cases, it is not easy to differentiate between subaquatic gliding, plume, density inversion, and seismicity features because these features can all be produced by ground agitation. Figure 7 show structures that most probably were produced by seismic agitation of the sediments.

7. STRUCTURES FORMED BY OVER-PRESSURIZED FLUIDS

Compaction of the fresh deposited, thinly bedded, fine-grained sediments of the Lisan Formation and its equivalent near-shore sediments lead to expulsion of their pore fluids. The vertical compaction of sediments due to additional sediment loads results in different permeability values between vertical and horizontal directions, where the horizontal permeability becomes higher than the vertical as a result of grains' horizontal layering. The horizontal pathways for pore

Figure 6. flexure structure in Lisan sediments, at the NE edge of the Dead Sea. Photo by Amaireh 2017

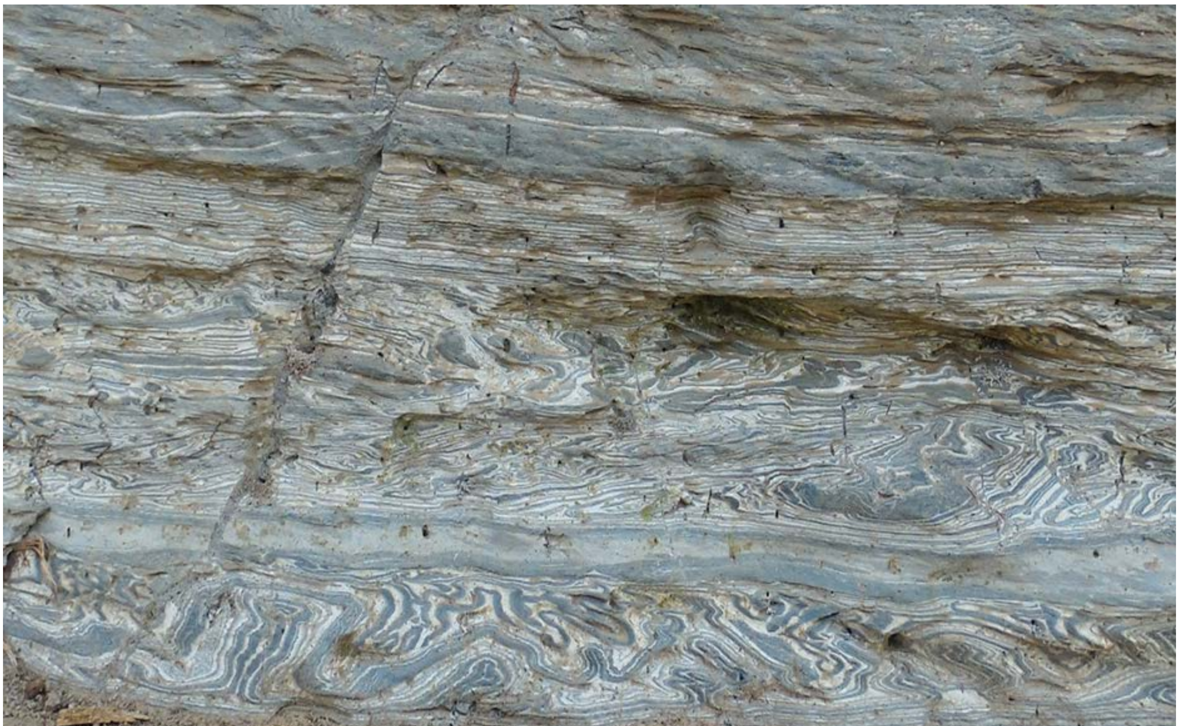

Figure 7. Seismites structure in Lisan Formation deposits.

liquids become more accessible than vertical ones, but fluid pressure within the sediments may build up to a certain degree and then suddenly be released causing strong disturbances in the semi-consolidated sediment packages.

Submarine groundwater seepages and springs may cause local over-pressurized segments in the recent semi-consolidated sediments, which pressure can reach a critical degree to explode at once creating great disturbances in the sediment layering and flow channels for the over-pressurized water.

Biotransformation of microbial-catalyzed reactions involving sulfate reduction produces gases such as H_2S and CO_2, which produce high fluid pressure in the sediments, which is added to the pressure caused by compaction due to additional sedimentation. The fluids try to escape in a horizontal direction along the high permeability horizons within the sediment package. But such pathways are long-distance and the fluids try to find their way out vertically through weakness zones forming herewith flow structures in the sediments in the form of plumes. Figure 8 shows such plume structures in the recently exposed Dead Sea sediments.

8. CONCLUSION

Recent rifting tectonics (Taphrogenic movements) in the area of the Jordan Rift Valley have been portrayed in a variety of sedimentary structures formed in the sub-recent sediments of the Dead Sea. These sediments have been recently evacuated from seawater due to the drop in the Level of the Dead Sea during the last 6 decades by around 35m.

These structures include Plumes and density inversions, subaquatic gliding, seismites, undulations and wavy structures, flexures, and overpressure structures. The formation of these structures is referred to different triggering effects such as:

- Earthquakes
- Tectonic activity
- Instability of slopes
- Density inversion
- Pore fluids overpressure resulting from gas production by biochemical processes within the sediments such as sulfur bacteria reduction of sulfates and oxidation of organic matter (petroleum residues)
- Over-pressurized pore water origination from surrounding groundwater submarine discharges
- Volume changes associated with the transformation of gypsum to basinite and anhydrite and the reversal of that transformation.

As a result of this study, the triggering factors, that produced the different meso-structures in the sub-recent sediments of the Dead Sea, have been elaborated. It has been shown that a triggering factor can produce more than one type of structure depending on the prevailing composition of the sediments, its layering attitudes, grain size distribution, porosities, and differential pressure situations within the sediment packages.

Figure 8. Over-pressurization of unconsolidated marls due to fluid-releases pressure resulting in the local flow of marls to enable escape of fluids horizontally and upwards.

The study recommends studying the ages of the discussed structures using isotopes, eventual implements, or others to correlate the structures to known triggering factors or to unknown ones, which may help explain other phenomena present in the Lisan sediments or other sediments in Jordan and which may have been caused by the same triggering factors.

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