

Tectonic Structures and Their Consequential Nontectonic Deformations

—The Case of the Friable Lower Cretaceous Sandstones in Jordan

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Abstract

The post Paleogene tectonic activities in the Levant comprising emergence of the Levant area from the Tethys Sea (epirogenic uplifts), the continuous drifting apart of the Arabian Plate from the African Plate along the Red Sea, and the taphrogenic movements (graben-tectonics) along the Jordan Rift Valley accompanied by uplifts of the Jordan Rift Valley eastern and western Shoulder Mountains have created a variety of major structures such as grabens, horsts, faults, strike slip faults, and flexures. Along these structures, and in their surroundings, nontectonic structures have developed with a variety of implications to the local and regional geologic set-up and topography. Such structures include formation of large topographic depressions, local faulting, block tilting, and flexuring, fine material flow channels along fractures and joints, dike fillings, density inversions, Local litho-stratigraphic pressure readjustments, and convolute bedding among others. This paper discusses the major regional tectonic structures in Jordan and their roles, together with other factors, in the formation of some nontectonic structures and the latter geologic, topographic and engineering geologic implications. After discussing the above issues, the article concludes that the exposure of the friable and easily erodible Lower Cretaceous sandstone along the major structures has created zones of geologic and topographic instability producing many types of nontectonic structures with a variety of consequences to land stability, topography, groundwater flow patterns, and fates of aquifers.

Keywords

Semi-Consolidated Sandstone, Physical Erosion, Chemical Erosion, Land Collapses, Secondary Nontectonic Structures Kurnub Sandstone

1. Introduction

The geology of Jordan has been the subject of hundreds of studies such as [1]-[4] and many others. This geology can be very shortly summarized as follows:

A Precambrian Granitic Basement cropping out in south Jordan and underlying the whole country started during Precambrian to be gradually covered by clastic sedimentary rocks originating from that Basement and its southern extension in Saudi Arabia and Egypt before the opening of the Red Sea (**Figure 1**). Thousands of meters of clastic rocks mainly consisting of sandstones covered that Basement (**Figure 2**). Progressively, from south to north Jordan, rocks of Precambrian to Jurassic ages crop out with missing Devonian, Carboniferous, and Early Permian. The Tethys Sea fluctuated and some marine sediments were included in places within that sedimentary package. During Lower Cretaceous, the Tethys Sea transgressed and mainly friable near-shore sandstones covered the northern part of Jordan up to the middle latitude of the Dead Sea and friable terrestrial clastics covered its southern part (**Figure 3(a)**, **Figure 3(b)**).

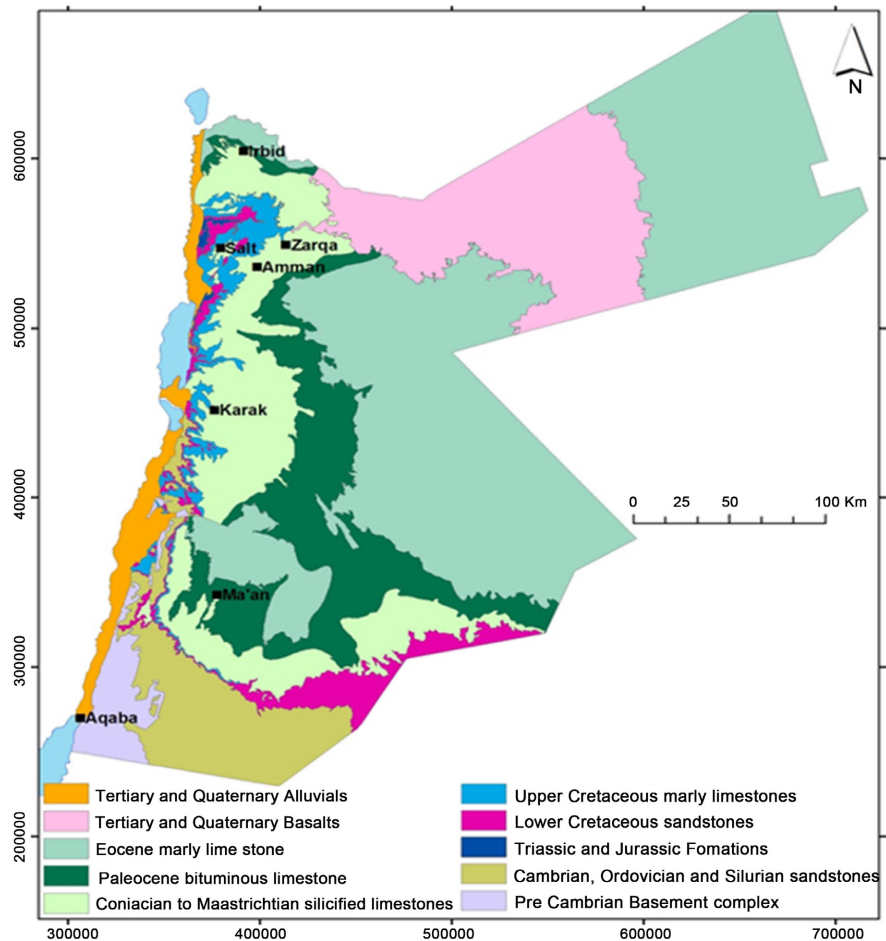


Figure 1. Simplified geologic map of Jordan¹.

¹NRA Natural Resources Authority, Geology Directorate, Geologic Mapping Division. Ministry of Energy and Natural Resources.

ERA	SYSTEM	EPOCH	GROUP	FORMATION	SYMBOL	LITHOLOGY	THICKNESS [m]	AQUIFER UNIT		
CENOZOIC	QUATERNARY	Holocene	JORDAN VALLEY (JV)	Alluvium	Qa1	clay, silt, sand, gravel		ALLUVIUM (AQUIFER)		
		Pleistocene		Lisan	JV3	marl, clay, evaporites	> 300			
	TERTIARY	Neogene	Pliocene	VALLEY (JV)	Samra	basalt	conglomerates	100 - 350	BASALT (AQUIFER)	
			Miocene		Neogene	JV1-2	sand, gravel			
		Paleogene	Eocene	BELQA (B)	Wadi Shallala	B5	chalky and marly limestone with glauconite	0 - 550	B4/5 (AQUIFER)	
			Paleocene		Umm Rijam	B4	limestone, chalk, chert	0 - 310		
MESOZOIC	CRETACEOUS	Upper	BELQA (B)	Muwaqqar	B3	chalky marl, marl, limestone chert	80 - 320	B3 (AQUITARD)		
				Amman-Al Hisa	B2	limestone, chert, chalk, phosphorite	20 - 140	A7/B2 (AQUIFER)		
				W. Umm Ghudran	B1	dolomitic marly limestone, marl, chert, chalk	20 - 90			
				Coniacian	AJLUN (A)	Wadi as Sir	A7	dolomitic limestone, limestone, chert, marl	60 - 340	A5/6 (AQUITARD)
				Turonian	Shueib	A5/6	marl, limestone	40 - 120		
		Lower	KURNUB (K)	Cenomanian	Hummar	A4	limestone, dolomite	30 - 100	A4 (AQUIFER)	
				Albian	Fuheis	A3	marl, limestone	30 - 90	A3 (AQUITARD)	
				Aptian	Naur	A1/2	limestone, dolomite, marl	90 - 220	A1/2 (AQUIFER)	
				Barremian	Subeihi	K2	sandstone, shale	120 - 350	KURNUB (AQUIFER)	
				Hauterivian	Aarda	K1	sandstone, shale			
	JURASSIC	ZARQA (Z)	PERMIAN	ZARQA (Z)	Azab		siltstone, sandstone, limestone	0 - >600	ZARQA (AQUIFER)	
					Ramtha		siltstone, sandstone, shale limestone, anhydrite, halite	0 - >1250		
					Hudayb		siltstone, sandstone, limestone	0 - >300		
	PALEOZOIC	SILURIAN	KHREIM (KH)	KHREIM (KH)	Alna		siltstone, sandstone, shale	0 - >1000	KHREIM (AQUITARD)	
Batra						mudstone, siltstone	0 - >1600			
Trebeel						sandstone	0 - 130			
Umm Tarifa						sandstone, siltstone, shale	0 - >1200			
Sahl as Suwwan						mudstone, siltstone, sandstone	0 - 200			
ORDOVICIAN		RAM (D)	RAM (D)	Amud		sandstone	0 - >1500	RAM SANDSTONE DISI (AQUIFER)		
	Ajram				sandstone	0 - ca: 500				
CAMBRIAN	RAM (D)	RAM (D)	Burj		siltstone, dolomite, limestone sandstone	ca: 120	RAM SANDSTONE DISI (AQUIFER)			
			Salib		arkosic sandstone, conglomerate	0 - >750				
PRECAMBRIAN	BASEMENT COMPLEX	BASEMENT COMPLEX	BASEMENT COMPLEX	Unassigned clastic unit		sandstone, argillaceous siltstone, claystone	0 - 1000	BASEMENT COMPLEX		
				Saramuj		conglomerate, sandstone	up to 420			
				Aqaba Igneous						

Figure 2. Stratigraphic column of Jordan with the rock types of the different formations, their lithologies, thicknesses, and aquifer characteristics [5].

A major Tethys Sea transgression took place at the end of the Lower Cretaceous, and calcareous Upper Cretaceous rocks were laid down covering all the area of Jordan except its most southwestern part, where the granitic Basement Mountains remained terrestrial domain. The Tethys Sea started its regression in Early Neogene and gradually, parts of Jordan, beginning from its southern parts, became

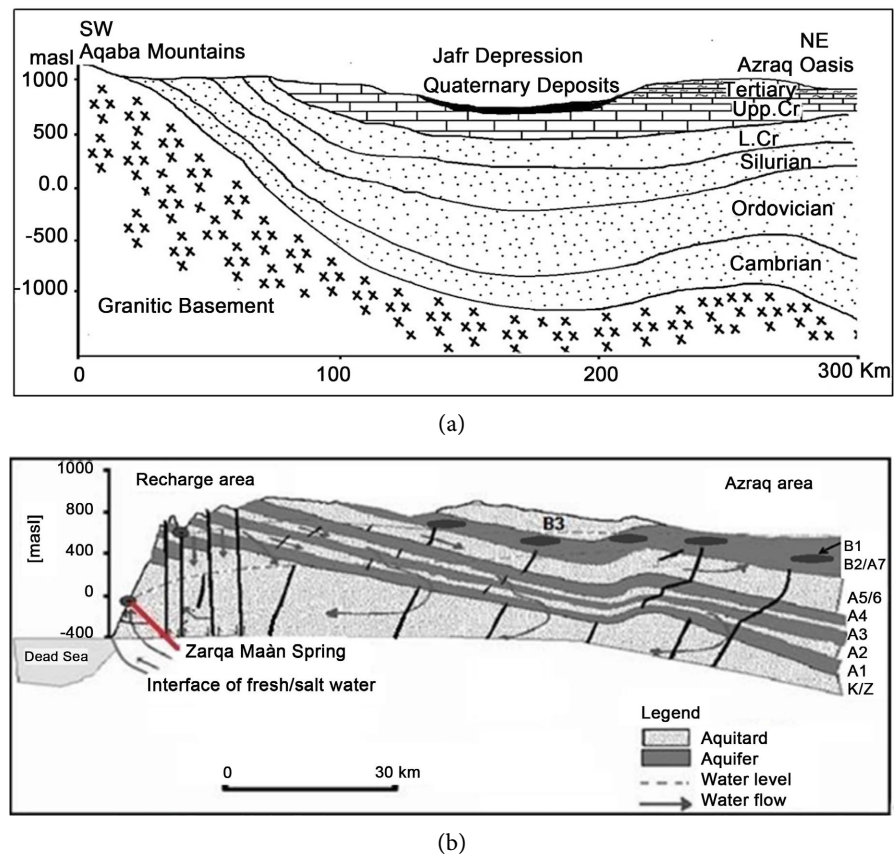


Figure 3. (a) A simplified Geological cross section from Aqaba in the southwest to Azraq in the north east. It shows the granitic Basement overlain by a thick series of clastic rocks of Cambrian, Ordovician Silurian and Lower Cretaceous ages overlain by a calcareous series of Upper Cretaceous rocks and in Azraq area, the latter is overlain by chalky limestone of Tertiary age [6]. (b) A simplified E-W geologic cross-section extending from the Dead Sea area in the west to the Azraq Oasis ca. 130 km in the east. It shows the general geologic set-up of the rock series in that part of the country and the complex groundwater flow system in the Upper Cretaceous-Tertiary calcareous rock series A1-A7 and B1-B3 and in the deep groundwater flow system in the clastic rock series K/Z and older (modified from) [7].

fest land. The retreat of the Tethys Sea and/or the epirogenic uplift of the Levant area were accompanied by reactivation of the Precambrian geosuture along the Jordan Rift Valley (JRV) causing the down-faulting of the Jordan Graben and the accompanying uplift movements of its Shoulder Mountains (Taphrogenic movements [3]). Simultaneously with the reactivation of the Jordan Geosuture and Rift Valley tectonics, SE-NW and E-W trending fault and graben structures resumed their tectonic activity or started their evolution. Such structures are Fayha-Karak Graben and Sirhan and Jafr Depressions trending NW-SE, Salawan, El-Hasa, Shihan, Swaqa, Zarqa Ma'in, Suweima-Hallabat, and Zarqa River faults trending W-E and gradually turning in east Jordan clockwise in a southeasterly course (**Figure 4**). In the JRV eastern Shoulder Mountains, the W-E trending faults are deep-seated affecting all the sedimentary sequence overlying the Granitic Basement. Of that entire sedimentary sequence, the Lower Cretaceous sandstone (Henceforth

the Kurnub Sandstone) consists of mostly friable, easily erodible sandstone.

Thick calcareous Upper Cretaceous rocks (in places > 1000 m) covered the friable Kurnub Sandstone with a thin transition zone of soft clay, marl, and glauconite [3]. When the latter became exposed at ground surface due to uplift movements (epirogenic and taphrogenic), faulting, fracturing, and erosion, the overlying calcareous rocks, together with the underlying soft-rocks of the transition zone started to be undercut and became unstable. That caused toppling, settlement and resetting of blocks, forming local geological structures, which expanded to form regional topographic and geologic nontectonic structures. None tectonic features are those not caused by large-scale movements of tectonic plates.

In the current work, the major regional tectonic structures in Jordan are described and their roles together with different other factors contributing to the formation of the nontectonic structures and the latter geologic, topographic and engineering geologic implications are elaborated. The article clarifies the question of how the nontectonic structures have formed and why only in specific areas in Jordan.

2. Major Tectonic Structures in Jordan

The geology of Jordan, as can be deduced from [3] [4] and many others, indicates that three main geologic structures together with the ingress and regression of the Tethys governed the geologic development of Jordan since Precambrian time. These geologic structures are the Precambrian Geosuture along the Jordan Rift Valley trending N-S, the Sirhan Depression at the eastern border of the country with Saudi Arabia striking SE-NW, and the Jafr Depression in southern Jordan also trending SE-NW (Figure 4). The types and ages of the sediments and their thicknesses within these three structures of many kilometers compared to their surroundings of up to 2 kilometers, give witness on the age and activity of these structures. Except activity along these three structures, Jordan seems to have been tectonically inactive until Early Neogene [2] [3]. The last regression of the Tethys Sea during Early Neogene was accompanied by differential epiprogenic and taphrogenic uplifts of the Levant producing block faulting. The vertical block faults start at the N-S striking Jordan Rift Valley, strike in a W-E direction and gradually turn, in east Jordan, after a few tens of kilometers, in a SE direction to merge into the major SE-NW-striking Jafr and Sirhan Depressions faults (Figure 4). In addition, some NNE-SSW to NNW-SSE trending weakness zones, which had developed during Precambrian time resumed their activity in Early Neogene (such as Shueib-Sweileh and Quweira faults). The main W-E faults are from south to north Salawan, El-Hasa, Shihan, Swaqa, Zarqa Ma'in, Suweima-Hallabat, and Zarqa River faults. Worth mentioning here is that all these faults are vertical, deep-seated, and active since Early Neogene affecting the entire sedimentary rock package including the Early Tertiary rocks. In addition, all these faults show dextral strike slip movements of a few kilometers.

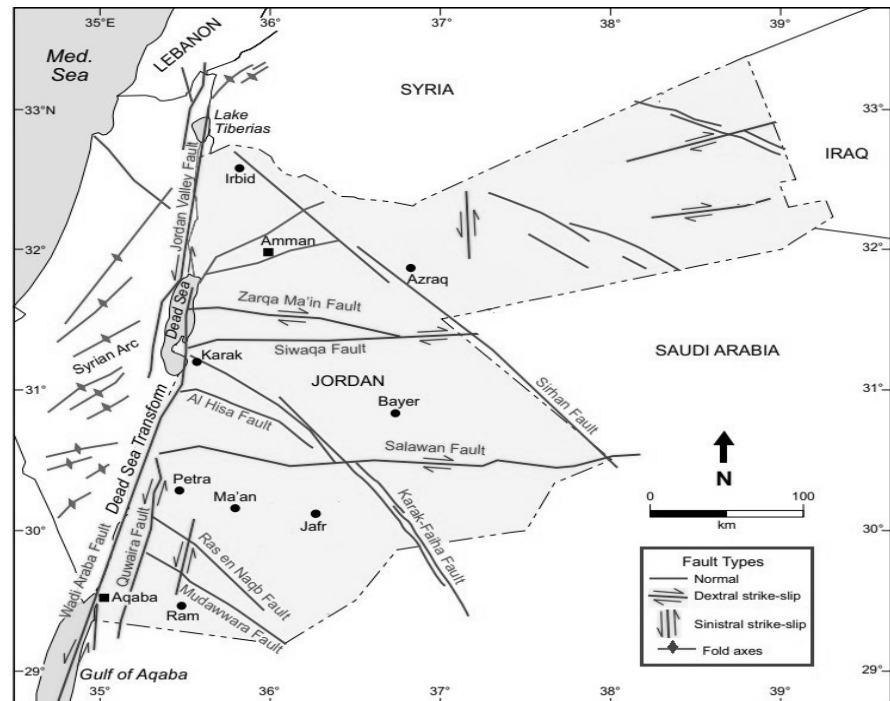


Figure 4. General structural geologic map of Jordan showing the major structural elements, which are mainly composed of faults along which lateral strike slip movements have and are taking place [8].

3. The Lower Cretaceous Sandstone (Kurnub Sandstone)

Tectonic activity portrayed in W-E trending, vertical to sub-vertical faults starting at the eastern foothills of the JRV and the uplift of the eastern Shoulder Mountains of the JRV accompanied by step faults striking parallel to the JRV exposed the friable Kurnub Sandstone at ground surface and created the conditions for the latter's erosion.

The outcropping of the Kurnub Sandstone along the escarpment of the Jordan Rift Valley and along the W-E trending faults have created outlets for the groundwater of the deep clastic, vertically and horizontally interconnected aquifer system built of Precambrian to Lower Cretaceous sediments [9] [10] (**Figure 1**, **Figure 3(a)**, **Figure 3(b)**). The exposure allowed for a variety of chemical and physical processes as discussed below:

Chemical erosion to erosion

The groundwater discharged from the Kurnub sandstone along the foothills of the eastern Shoulder Mountains of the JRV (Afra, Weda'a, Ibn Hammad, Zara, Zarqa Ma'in, Suweima, Deir Alla and others, **Figure 5**) is thermal containing SiO_2 in concentrations of generally 27 - 31 mg/l (**Table 1**) [11]-[16]. The temperatures of the cold groundwater of the overlying Upper Cretaceous aquifers (the source of the Kurnub groundwater) range from 26°C - 35°C and its groundwater contains SiO_2 in concentrations of 8 - 10 mg/l [12] [16].² Such concentrations are in

²MWI: Ministry of Water and Irrigation, Central Laboratories. Open files.

equilibrium with respect to the groundwater temperatures. Therefore, the additional SiO_2 in the Kurnub water must originate from the dissolution of the quartz grains of the Kurnub silicic rock matrix, caused by increasing releases of SiO_2 due to increasing temperatures [17]-[19]. The Kurnub groundwater has reservoir temperatures of 75°C - 90°C [11] [19]-[26], compared to a temperature of the overlying calcareous aquifer of 26°C - 32°C increasing in some wells to 42°C (Table 1). The silica content of the Kurnub aquifer water remains in metastable equilibrium in aqueous form despite the drop in the water temperature, which accompanies the groundwater flow to its discharge sites [26]. The dissolution and release of SiO_2 from the surface of the quartz grains leads to reduction in their volumes and hence to increased looseness of the rock matrix, which enhances their erodability and transportation by the flowing groundwater, especially near the groundwater discharge sites at ground surface. Worth mentioning here is that SiO_2 in water is found in aqueous and not ionic form, which means that the common ion effect and ionic strength of the water solution play no major role in the concentration of SiO_2 in water and solution temperature remains the sole player.

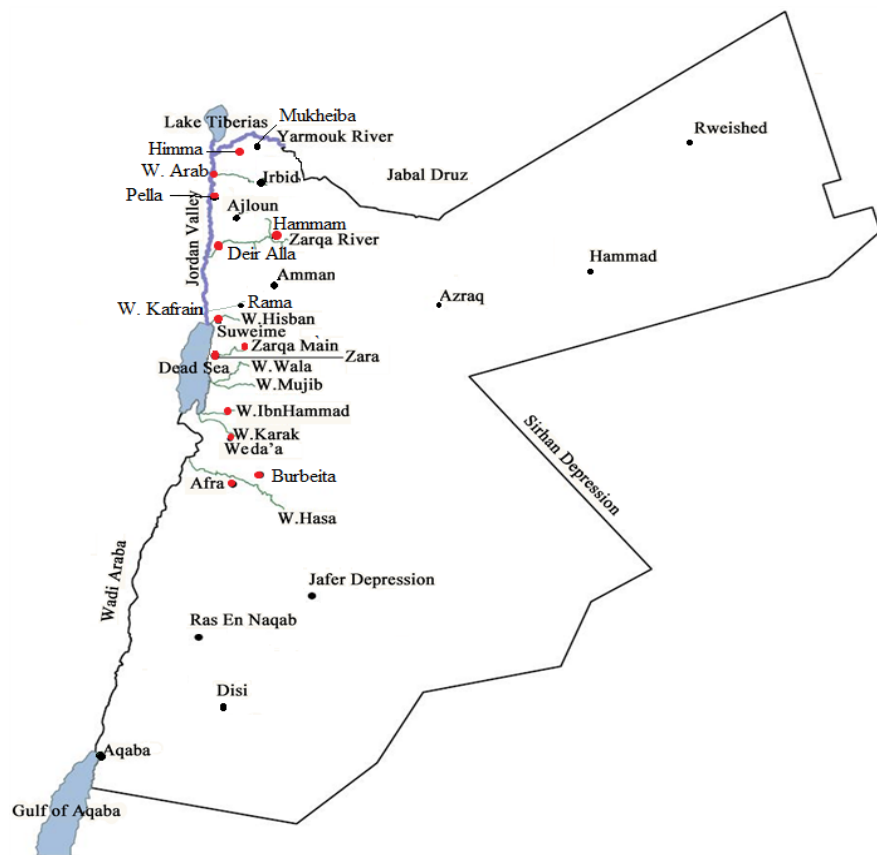


Figure 5. Locations of the main thermal spring discharge sites in Jordan (Red dots). They are concentrated along the eastern side of the Dead Sea and the Lower Jordan Valley.

The National Water Master Plan of Jordan and its updates [27] calculated the quantity of the thermal water discharged from the thermal springs in the area ex-

tending from Wadi El-Hasa in the south to Suweima in the north at around 80 MCM/yr (**Figure 5**). Salameh and El-Nasser [28] [29] calculated the surface and submarine (into the Dead Sea) discharges at around 150 MCM/yr (excluding the enhanced groundwater outflows due to the recent drop in the Dead Sea level [28]) [29]. That allows us to estimate the annual quantity of released dissolved SiO₂ from the rock matrix, which leaves the Kurnub aquifer at 3000 tons a year. That is in addition to the huge quantity of sand particles, which leave the aquifer with the discharged water because of solid particles erosion.

Table 1. Composition of the water of the silicic deep aquifer (Kurnub) thermal springs and the shallow calcareous aquifer (B2/A7) east of the Dead Sea.

Area Variable/Site	Zarqa Ma'in K		Khan El-Zabeeb K	B2/A7	
	Al-Shallal	Al-Amir	Well no. 4J	Hakam Al-Fayez	Anwar Khamis
EH-value	15.8	18.9	37.0	na	na
Temp °C	56.6	48.6	65.2	30	39.0
pH-Value	6.3	6.2	6.25	7.0	6.9
EC µS/cm	3051	3080	2670	875	1417
TDS mg/L	2279	2346	1456	429	657
Na ⁺ meq/L	19.52	18.63	15.0	1.61	5.40
K ⁺ meq/L	1.11	1.32	0.60	0.08	0.11
Mg ²⁺ meq/L	3.22	3.41	2.25	2.57	3.53
Ca ²⁺ meq/L	7.23	7.82	5.93	3.97	5.51
Cl ⁻ meq/L	21.52	22.32	19.31	1.69	4.97
NO ₃ ⁻ meq/L	0.1	0.05	0.0	0.07	0.0
SO ₄ ²⁻ meq/L	3.82	3.93	2.90	1.16	5.00
HCO ₃ ⁻ meq/L	4.8	4.82	2.73	5.03	4.72
CO ₃ ²⁻ mg/L	215	224	na	na	na
F ⁻ mg/L	0.31	0.43	0.47	0.50	1.12
Br ⁻ mg/L	7.74	7.21	2.18	0.44	0.53
I ⁻ mg/L	0.11	0.08	na	na	na
TC meq/L	31.1	31.2	na	na	Na
Fe mg/L	0.09	0.23	1.77	0.02	0.03
Mn mg/L	0.6	0.79	0.86	0.01	0.02
H ₂ S mg/L	0.2	0.16	na	smell	Smell
SiO ₂ mg/l	28.5	30.4	35.0	9.5	17.4

Physical erosion

Sand deposited along the flow courses of the thermal water spring indicates at the recently eroded sand from the rock matrix. Recent, as well as, old travertines deposited from the thermal water springs, in addition to the iron- and manganese-rich dike fillings in the Kurnub Sandstone are mainly composed of quartz grains, which had eroded from the Kurnub Sandstone (**Figures 6(a)-(c)**).

Earthquakes and vibrations cause some movements, agitation, and liquefaction of sand grains, when the sand is friable and especially when it is hydrostatically over-pressurized (liquefaction), which is the case of the Kurnub Sandstone and as the upward-directed flow channels in it indicate (Figure 7). The over-pressure of the Kurnub aquifer, comes as a result of a far higher hydrostatic groundwater level of the upper aquifer separated from the Kurnub aquifer by poor-primary permeability and adequate secondary permeability layers.

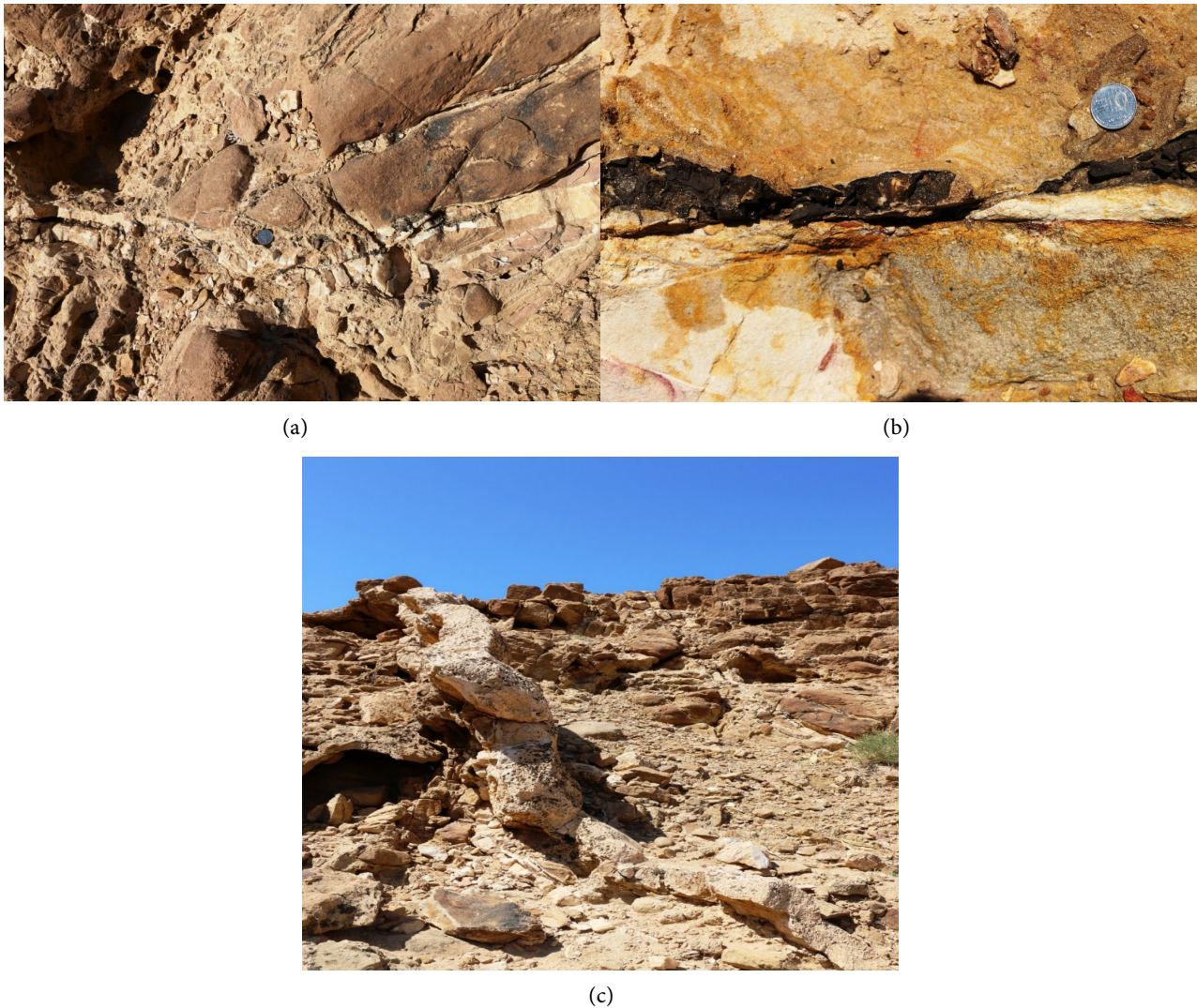


Figure 6. (a) Openings filled with sand eroded from the Kurub Sandstone Unit. In places cemented by calcite; (b) Openings filled with sand cemented by calcite and containing metal oxides (mainly iron and manganese) eroded from the Kurnub Sandstone Unit, before it was flushed out of these oxides; (c) Joints filled with white travertine containing sand grains eroded from the, of metal oxides- flushed, Kurub Sandstone Unit.

Calcareous Upper Cretaceous formations overlie the Kurnub Sandstone, in places with a transition zone of clay, marl, and glauconite (Bandel and Salameh 2013, Bender 1968), which all have densities of around 2.7 g/cm^3 exceeding that of the sandstone of $1.9 - 2.1 \text{ g/cm}^3$. Due to that and assisted by agitation as a result

of ground movements, pieces and small blocks of the weakly cemented Kurnub Sandstones migrate upwards into the higher density marls and clays substituting them (density inversion) (**Figure 8**).



Figure 7. Agitation and liquefaction of the friable Kurnub Sand under hydrostatically over-pressurized conditions (liquefaction), as the upward-directed flow channels indicates (Picture middle).



Figure 8. Upward migrating of low-density (1.9 - 2.1 g/cm) sandstone pieces of upper most Lower Cretaceous rocks through the higher density (2.7 g/cm) clays and marls of the transition zone to the Upper Cretaceous calcareous rocks (Jordan Road, Al-Rumman area).

The Kurnub Sandstone, including the transition zone to the Upper Cretaceous rocks, exposed at ground surface in outcrops or along weakness zones such as joints and faults, erode easily by rainwater, groundwater discharges, wind, earth vibrations, boring animals, and plants, whereas, the overlying calcareous Upper Cretaceous rocks build continuums (solid blocks) separated by joints. When the underlying sandstone erodes and undercuts the calcareous blocks, the limestone blocks topple down exposing additional parts of the underlying sandstone to erosion and that process progress with the passage of time (**Figure 9**).



Figure 9. Toppling of Upper Cretaceous limestone beds resulting from the undercutting of the underlying semi consolidated Lower Cretaceous sandstone and the soft sediments of the transition zone from the Lower Cretaceous to the Upper Cretaceous.

Types of features created by erosion of the Kurnub sandstone

Three genetically related types of geologic and geomorphologic features have developed as caused by the erosion of the Kurnub Sandstone.

Type 1: The extended Baqa'a topographic depression is an example of this type. It started at the NNE-SSW striking Shueib-Suweileh Flexure, along parts of which the Kurnub Sandstone became exposed to erosion, which caused undercutting, tilting and toppling of the overlying calcareous rocks. That process progressed with time to create a topographic depression in the Plateau area of Jordan extending for about 10 km in a NNE-W direction along the Shueib-Suweileh Flexure and about 4 km in ESE-WSW direction (**Figure 10**).

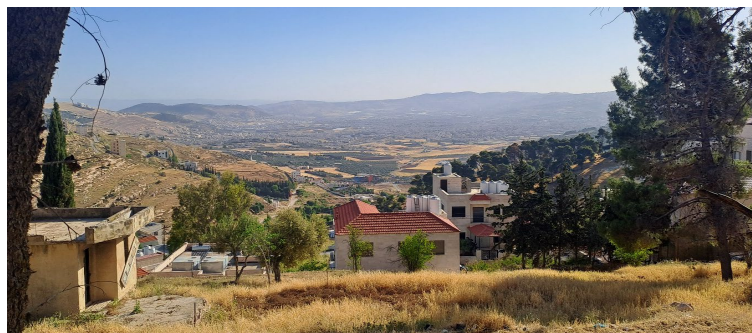


Figure 10. Photo of Baqa'a topographic depression formed along the NNE-SSW striking Suweima-Suweileh compressional flexure (on the left side), It is mainly caused by the erosion of the semi-consolidated Kurnub sandstone leading to the undercutting of the overlying intact limestone beds (NNE-SSW 10 ~ km, SSE-NNW ~ 4 km).

The case of Baqa'a topographic depression represents an advanced stage of what the erosion of the Kurnub Sandstone along faults will produce in the mountainous

areas of Jordan (Figure 11).

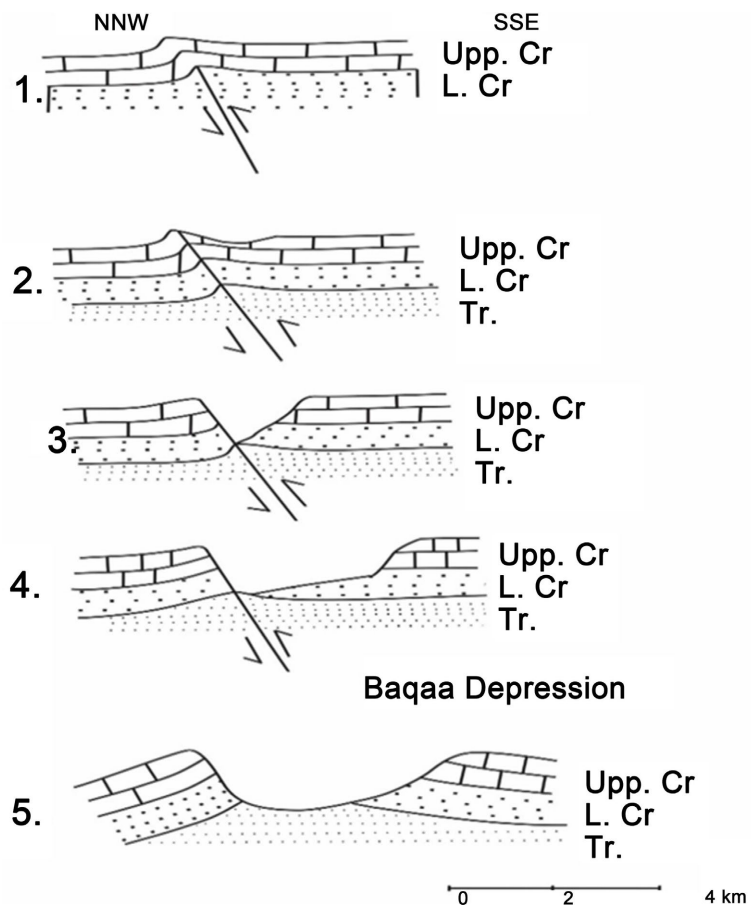


Figure 11. Development of the Baqaa topographic depression because of combined tectonic and erosional activities. 1): Flexure formation along a NNE-SSW. 2): Formation of a water channel which enhances erosion along its course, which widens and deepens. 3) Erosion with the passage of time and with continuing tectonic activity along the fault. 4): When the erosion of the Lower Cretaceous semi-consolidated sandstone started, rock toppling in the overlying solid limestone blocks exposed more sand for fast erosion. 5): Schematic SSE-NNW geologic cross-section of Baqaa Depression (Upp. Cr.: Upper Cretaceous, L. Cr.: Lower Cretaceous, Tr. Triassic).

Type 2: The groundwater in the Kurnub Sandstone originates from the direct recharge into the overlying Upper Cretaceous and Tertiary aquifers and its down-percolation into the Kurnub Sandstone. The geologic and topographic restriction of the discharge sites of the Kurnub Sandstone groundwater to certain sites, forces its groundwater body as a whole to accumulate and become confined with piezometric heads lower than those resulting from the lithostatic pressure of the overlying confining layers. In some areas, because of faulting and jointing, the confined Kurnub groundwater has found its way to ground surface along faults and joints, carrying with it the eroded sand grains, which temporarily settle along the surface water flow channels (Figure 12). Accordingly, the thickness of the Kurnub Sandstone reduced and the overlying calcareous blocks became undercut

and toppled down. Upon that, the overlying calcareous rock blocks settled to fill the space creating a type of shallow graben structures formed along the E-W regional faults.

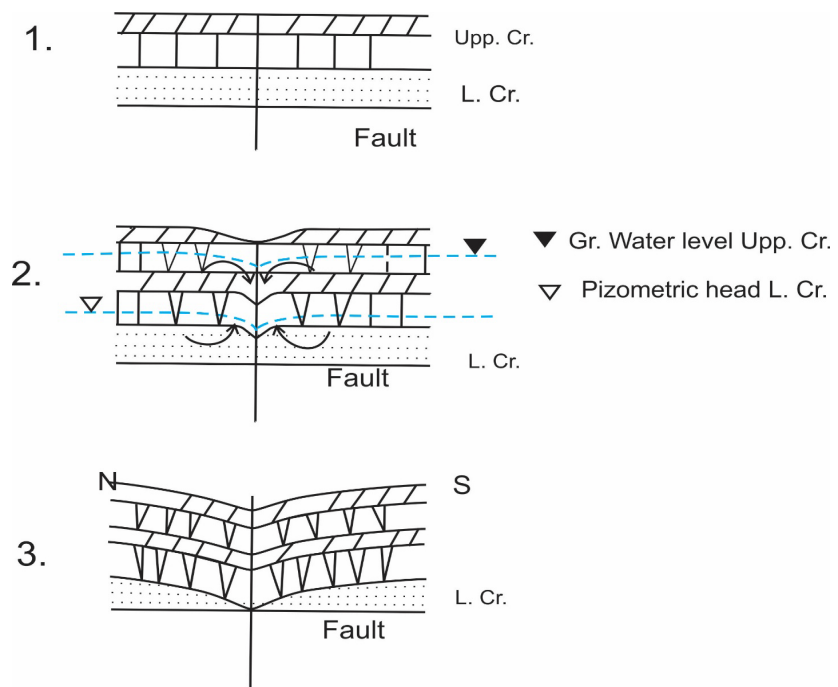


Figure 12. Erosion of the Lower Cretaceous semi-consolidated sandstone by the emerging thermal confined groundwater reducing the volume of the sand stone and causing the settlement of the overlying solid limestone blocks. 1) W-E striking vertical faults (Initial stage). 2) Erosion of the friable Lower Cretaceous sandstone by the emergence of the confined groundwater in the Lower Cretaceous along the fault line accompanied by the collapse of the overlying limestone blocks. 3) Collapse of the calcareous Upper Cretaceous rock package and formation of local secondary faults trending E-W parallel to the main fault and other faults trending N-S perpendicular to it.

Type 3. Along the JRV eastern escarpment and its side wadis, the erosion of the friable Kurnub Sandstone and the toppling of the overlying intact blocks of limestone have different consequences on the geologic and topographic configurations. This can be observed in: Humrat Ma'in (West of Madaba City), Humrat El-Sahn (Northwest of Salt City), Humrat Fidan (West of Tafila City), and Mahis areas (Figure 13). The erosion of the sandstone causes undercutting of the overlying calcareous rocks, which topple down with time and expose new areas of the sandstone to erosion. The topographic consequence are flat topographies of the eroded Kurnub Sandstone covered with scattered falling blocks from the overlying, steeply-cliffing calcareous Upper Cretaceous rocks prone to tilting and toppling (Figure 13).

Secondary structures

As discussed in type 2 above, the Kurnub groundwater finds its way to ground surface along the N-S striking escarpments. In addition, it also discharges along

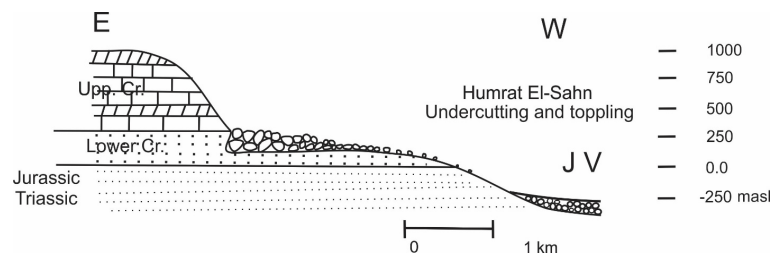


Figure 13. Erosion and Toppling along the cliffs of the Jordan Rift Valley composed of Lower Cretaceous semi-consolidates sandstone overlain by hard intact blocks of limestone.

the main W-E striking faults (Hasa, Ibn Hammad, Mujib, Shqeiq, Zarqa Ma'in, Zarqa River etc.) herewith causing in places differential erosion of the sandstone and reduction in its thickness, which leads to differential settlement, tilting and sliding of the overlying calcareous rock blocks along faults striking \pm perpendicular to the W-E faults (Figure 12).

The \pm N-S faults and jointing system developed, because of the erosion of the sandstone, secondary weakness zones with maximum downthrows along the main W-E faults, which die out in both southerly and northerly directions perpendicular to the E-W striking main faults (A type of N-S scissor faults). At ground surface these local secondary faults are manifested in tilted low throws' horst and graben structures striking \pm N-S with lengths of generally a few tens to a few hundreds of meters. A good example on that is Zarqa Ma'in fault, which appears to strike in a type of zigzag E-W course due the local differential downthrows (differential sinking and settlement of blocks) along the secondary pseudo-, N-S faults. In addition, El-Hasa Graben [30] is another example, where graben-/horst-similar structures start at El-Hasa E-W fault and die out in a southerly direction. These local semi horst and graben structures have originally established themselves in the Kurnub Sandstone and not in the underlying rocks. Later on, they affected all overlying Upper Cretaceous calcareous rocks.

4. Conclusions

The friable nature of the Kurnub Sandstone, its confined groundwater, the regional faulting pattern, in addition to its elevated groundwater temperatures leading to increased SiO_2 releases from the rock matrix are factors that enhance surface and underground erosion of the friable Kurnub Sandstone. This erosion has further consequences to the continuity of the overlying calcareous rocks, such as undercutting, disintegration, settlement, tilting and toppling of the calcareous intact rock blocks, formation of topographic depressions, local faulting, and upward-oriented water flow channels containing eroded sand grains along joints and fractures. In addition, the consequences include filling of dikes in the Kurnub sandstone and in its overlying calcareous rocks with sand grains cemented by carbonates and iron-manganese oxides. Worth mentioning here is that the Kurnub groundwater becomes oversaturated with these minerals upon contact with the

atmospheric air where carbonates precipitate [20] [21] [23].

The differential erosion and removal of huge quantities of sand grains and SiO₂ in aqueous form from the Kurnub rock matrix reduced the volume and the thickness of the sandstone package, which has other consequences on the continuity of the overlying calcareous rocks. Reduction in the thickness of the Kurnub rocks causes some overlying calcareous blocks to settle down differentially along the E-W faults to form a type of local graben and horst structures, which die out in southerly and northerly directions. Along the E-W oriented faults, disturbances in the continuity of the blocks take place (in addition to their horst-graben structures) in the form of down-thrown small blocks along secondary E-W oriented block borders, herewith destroying the original continuity of the tectonic E-W striking regional faults. Erosion of easily erodible sandstone overlain by intact rocks produced in Jordan and elsewhere in the Levant a unique variety of structural and topographic features, which cannot be related to tectonism such as Baqaa topographic depression in Jordan and Maqtash Ramon in Israel [31].

The nontectonic structures have rigorous landscape, hydrogeological and engineering consequences in Jordan expressed in land collapses, landslides and spring sites changes.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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