

On the Origin and Evolution of the Petra Siq from Geological Perspective, Is It Natural or Man Made?

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Abstract

Ancient Petra is predominantly carved in the colorful, hematitic, quartz sandstone of the Late Cambrian Umm Ishrin Formation with minor activity within the white quartz sandstone of the Early Ordovician Disi Formation. The entire length of the Siq also runs through the former rock unit. This article seeks to demonstrate through geological evidence that the Siq originated and developed naturally by means of normal geological processes and is not man-made. To achieve this goal, 38 trends of the bends of the Siq and more than 1100 joint trends were measured with a geological compass in the Siq and its surroundings. Rose diagrams of this data show that the major trends of the bends of the Siq of 60-70 and 150-160 degrees coincide almost exactly with the major trends of the joints of 60-70 and 140-150 degrees with the major class at 150-160 degrees. This means that the flood water of Wadi Musa has acted on the two major joint sets, eroding and enlarging them to form the Siq. Simple calculations of the rate of erosion tentatively indicate that erosion of the Siq might have started some 2 million years before present, long before the arrival of the Nabataeans.

Keywords: Petra, Siq, Joints, Water erosion, Cambrian, Sandstone, Jordan.

Introduction

Petra is associated with the Nabataeans, an Arab tribe who migrated from Arabia and settled there, most probably around the 6th century BC. By around the 2nd and 1st centuries BC, Petra was glorious as the capital of the Nabateans, whose rule extended from Damascus in the north to Mada'in Saleh in NW Arabia in the south. Petra served as a route for trade between east and west. Most of the

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monuments were been built during these two centuries. Petra was conquered by the Romans in 106 AD at the time of the Emperor Trajan. Afterwards it started to decline. For a detailed history of Petra and the Nabataeans, see for example Hammond (1973), Taylor (2001), Zayadine (2001), Graf (2003), Nasarat and Twaissi (2010).

The Siq is a long, narrow fissure in the sandstone rocks that form the entrance to the carved ancient city of Petra. During several visits to Petra, certain workers there claimed that the Siq was dug by the Nabataeans with no role for natural geological processes in making it. They tried to defend their idea by noting the presence of some man-made carvings on the walls of the Siq. However, detailed geological investigation shows that the contrary is true and the Siq must be natural, produced by geological processes that affected the sandstone rocks for a long geological period. The role of the Nabataeans was only to utilize a pre-existing fissure as an entrance to their city. The aim of this paper is to give detailed geological evidence on the origin, evolution and possible timing of its formation.

2. Geological setting

2.1 Location and topography

The ancient city of Petra is located about 270 km south of Amman and 133 km north of Aqaba on the edge of the mountainous desert of Wadi Araba between the coordinates 30°19'43"N and 35°26'31"E (Fig. 1). Topographically, the area is a rugged mountainous area with an altitude of 1443 m above sea level at the Wadi Musa town decreasing to 1100 m at the Visitor's Centre, 1000 m at the entrance of the Siq and around 900 m near Qasr al-Bint towards the western reaches of ancient Petra.

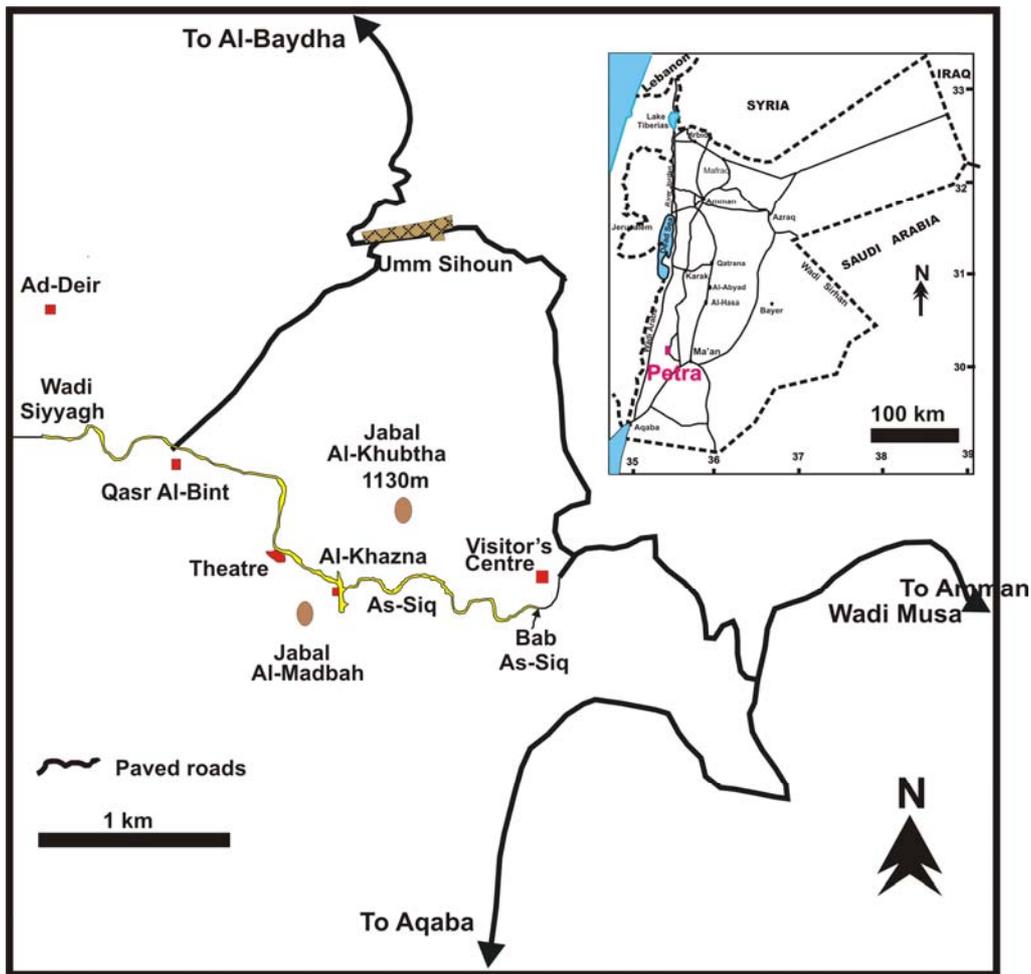


Fig. 1 Location map of the Petra-Wadi Musa area and the position of the Siq. A map of Jordan is shown as an inset.

2.2 Stratigraphy

Petra was carved in two geological formations: the Umm Ishrin Formation in which most of the monuments are found and the Disi Formation with minor carving activity. Table 1 summarizes the nomenclature of the rock units within the Ram Group that partially crops out in the Petra area.

Table 1: Nomenclature of the Paleozoic Ram Group by various authors

NRA, 1984		Lloyd 1969 Formation	Bender 1974 Units	Quennell 1951, Burdon 1959	Age
Group	Formation				
RAM	Um Sahm	Um Sahm	Bedded Brownish Weathered Sandstone		Lower Ordovician 495-470 Ma
	Disi	Disi	Massive Whitish Weathered Sandstone	Rum Sandstone	
	Umm Ishrin	Um Ishrin	Massive Brownish Weathered Sandstone	Upper Quweira Sandstone	Upper Cambrian 505-495 Ma
	Abu Khusheiba Burj		White Fine Sandstone Dolomite. Shale Limestone	Burj Limestone Group	Middle Cambrian 520-505 Ma
	Saleb	Saleb	Bedded Arkosic Sandstone Basal Conglomerate	Lower Quweira Sandstone	Lower Cambrian 543-520 Ma
Araba Complex			Precambrian	Aqaba Granitic Complex	600-540 Ma
Aqaba Complex					800-600 Ma

2.2.1 Umm Ishrin Formation

The name is taken from Jabal and Gaa Umm Ishrin in the Ram area (Lloyd, 1969). It was called the “Massive Brownish Weathered Sandstone Unit” (Bender

(1974). It consists predominantly of quartz arenite or quartz sandstone cemented by iron oxides. Small quartz pebbles are present especially at its lower part, while a few beds of siltstone and mudstone can be seen at the upper part. The whole formation is made of massive, multicolored (yellow, grey, red, brown and mauve-red) fine, coarse to medium-grained, cross-bedded sandstone (Fig. 2). Planar and trough cross-bedding is typical. Overtuned cross-bedding is common within the formation. The thickness of the formation is 300-350 m. Its age is Late Cambrian. The depositional environment of the formation was in a fluvial braided river system (Selley, 1970, 1972; Amireh, 1987, Powell, 1989a; Abed, 2000). The formation is underlain by the lower Cambrian, pebbly, arkosic sandstone called the Saleb Formation (few metres only). The Saleb Formation overlies the Precambrian igneous basement of the Araba Complex (Rashdan, 1988; McCourt and Ibrahim, 1990; Jarrar, 1992). The latter two rock units are not described here because they far to the west of the Siq. Fig. 3 shows a generalized columnar section showing the stratigraphy of the rock units in the Siq area.



Fig. 2: Photo from inside the Siq showing the typical colors of the Umm Ishrin Sandstone Formation and some joints inclined to the Siq (arrows).

The Umm Ishrin Formation crops out in most parts of the Petra area, and the upper and lower boundaries of the formation are easily distinguished in the field and aerial photographs. The geomorphologic features, the lithological homogeneity and the distinct joint system are the most characteristic elements in the field, while on aerial photographs it is clearly identified by its medium-dark tone, massive morphology, steep cliffs and dense fracture system.

Long vertical joints, crossing the whole formation, are one of its most distinguishing features not only in the Petra area, but also in the Ram area. In the latter area, beautiful columns are produced by the weathering of the joints, providing Lawrence of Arabia with the title of his book *The Seven Pillars of Wisdom* (Lawrence, 1940).

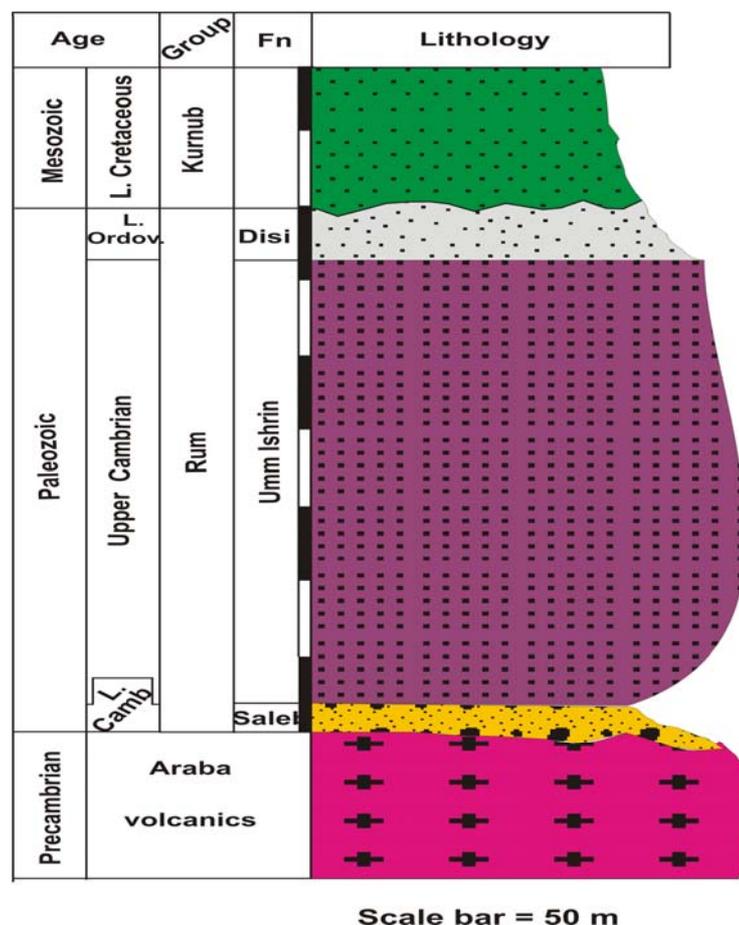


Fig. 3: Columnar section of the rock units cropping out within and near Petra.

2.2.2 Disi Formation

The formation is named after Gaa' Ed Disi in the Ram area (Lloyd, 1969). It is the "Massive White-Weathered Sandstone Unit" of Bender (1974). The Disi Formation overlies the Umm Ishrin Formation and consists of almost pure white quartz arenite or quartz sandstone with minor cementing material of kaolinite and dickite (Amireh, 1987). The sandstone is medium to coarse grained with quartz pebbles frequently seen at the base of the cross bed sets. The formation is distinguished by its white colour, large scale trough cross bedding, and dome appearance after weathering (Fig. 4).

The Disi Formation crops out just above the Visitor's Centre down to the entrance of the Siq. The formation is around 300 m thick in its type locality in the Ram area, whereas only the lowermost 50 m or so are present east of the Siq where some monuments are carved into it. It is lower Ordovician in age and was deposited by a braided river system ((Selley 1970, 1972; Bender 1974; Amireh, 1987; Powell, 1989a).

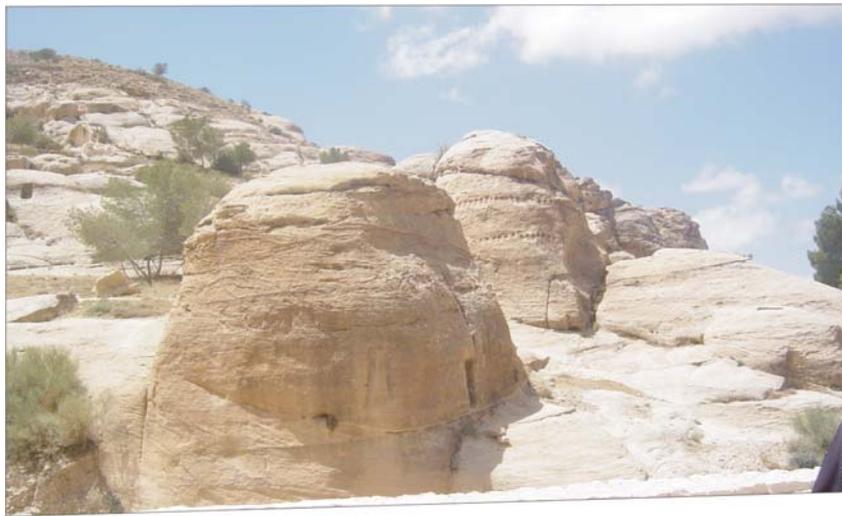


Fig. 4: Field photo of the Disi Sandstone Formation midway between the Visitor's Centre and Bab as-Siq.

2.2.3 Kurnub Group:

The Kurnub Group is not associated with any Petra monuments or carving. It crops out further to the east towards the base of the eastern mountains. The group

is Early Cretaceous in age, 145-100 million years (Ma), meaning that it overlies the Disi Formation with a prolonged unconformity of erosion and non-deposition (Fig. 3). The group consists of massive white sandstone at the base followed upwards by a varicoloured sandstone unit at the top. It consists of rather friable quartz arenite of fluvial origin (Abed, 1982; Amireh, 1997).

2.2.4 The Carbonate Regime

By the beginning of the Upper Cretaceous, around 100 Ma, the Tethys Ocean transgressed over the whole Eastern Mediterranean, including Jordan. Almost all of Bilad ash-Sham became part of the southern continental shelf of the Tethys Ocean. Consequently, carbonates (limestone, chalk, dolomite and marl) dominated the deposited sequence with bedded chert and phosphorite. The carbonate regime continued up to the end of the Eocene some 35 Ma ago. This period is represented by the Ajlun and Belqa Groups several hundred metres thick (Masri, 1963; Quennell, 1951; Powell, 1989b; Barjous, 2003). This carbonate sequence starts from the lower reaches of Wadi Musa town and continues further east, northeast and southeast. It was not associated with the carvings and monuments of ancient Petra and is mentioned here for the sake of completeness.

2.3 Geological Structures

Geological structures in the Siq and its surroundings are represented by faults and joints. Such structures are due to stresses related to the tectonic activities that affected the area in the geological past.

2.3.1 Faults

Faults are fractures in the rocks that involve a movement of one block of the fractured rock relative to the other. Two major faults trending NE-SW are present further west of the Siq, creating a graben there. Few inferred local faults trending NW-SE, to NNW-SSE are reported crossing the Siq and the nearby area (Fig. 5). One certain fault, trending NW-SE, is present at the entrance of the Siq, putting the Umm Ishrin Formation against the Disi Formation. It should be emphasized that there is no one single fault present along the Siq; i.e. the Siq is not the

manifestation of faulting. Fig. 5 is a geological map of the Siq and its surroundings showing the geological formations described above as well as the inferred faults crossing the Siq (Modified after Jaser and Barjous, 1992).

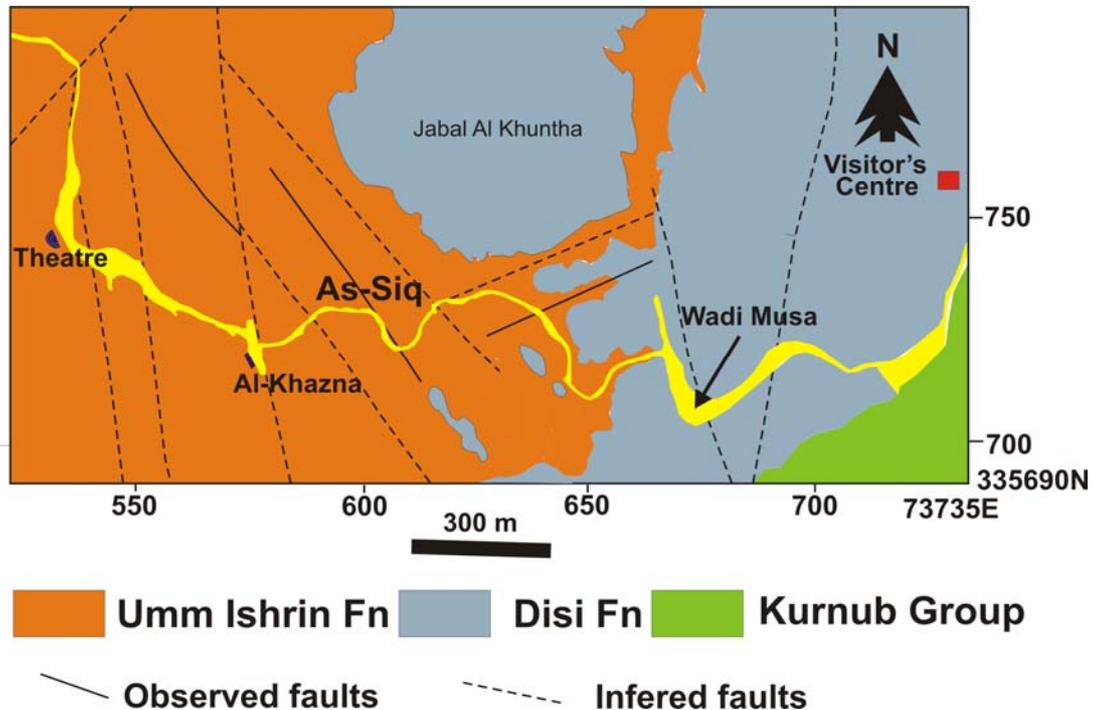


Fig. 5: Geological map of ancient Petra showing the formations cropping out in the area, faults, the Siq, some important monuments and part of Wadi Musa (Modified after Jaser and Barjous, 1992).

2.3.2 Joints

Joints are fractures in the rocks that do not involve a movement of one block of the fractured rock relative to the other. Joints are also produced by the stresses affecting the strata involved in the tectonic activities. The Umm Ishrin Formation is well known for its long vertical joints (Fig. 2). In fact, long vertical joints are characteristic of the Umm Ishrin Formation where ever it is exposed. Joints in the Umm Ishrin Formation are discussed further below.

3. Methodology

By means of conventional geological methods, the Siq was mapped for its

stratigraphy, faults, joints and bends. A geological compass was used to measure joint attitudes within the Siq and its surroundings. Attitudes or directions of Siq bends were also measured using the same technique. Traditional rose diagrams were used to plot the joint and bend data obtained.

4. Results

Because the Siq is present within the Umm Ishrin Formation only, more than 1100 joint attitude measurements were carried out in the formation and summarized in Table 2. The trends or directions of the bends of the Siq are shown in Table 3.

Table 2: Summary of trends of 1136 joints measured in the Umm Ishrin Formation within the Siq and its surroundings

Range of trends	Counts	Range of trends	Counts
0° - 10°	52	91° - 100°	8
11° - 20°	2	101° - 110°	4
21° - 30°	8	111° - 120°	16
31° - 40°	4	121° - 130°	44
40° - 50°	42	131° - 140°	100
51° - 60°	118	141° - 150°	86
61° - 70°	184	151° - 160°	128
71° - 80°	176	161° - 170°	68
81° - 90°	62	171° - 180°	34

Table 3: Summary of the 38 trends of the Siq bends

Range of Siq bends	Counts	Range of Siq bends	Counts
0° - 10°	0	91° - 100°	1
11° - 20°	3	101° - 110°	4
21° - 30°	3	111° - 120°	1

Range of Siq bends	Counts	Range of Siq bends	Counts
31° – 40°	1	121° – 130°	1
40° – 50°	1	131° – 140°	1
51° – 60°	2	141° – 150°	0
61° – 70°	7	151° – 160°	6
71° – 80°	1	161° - 170°	1
81° - 90°	5	171° - 180°	0

5. Discussion

The Siq is a fissure-like opening within the Umm Ishrin Formation. It runs roughly in an E-W direction with a width range of 3-16 m, a length of 1.2 km and a height of several tens of metres depending on the location. It is not a straight E-W line, rather it bends and meanders several times to the north and south of its main direction (Figs. 1 and 6).

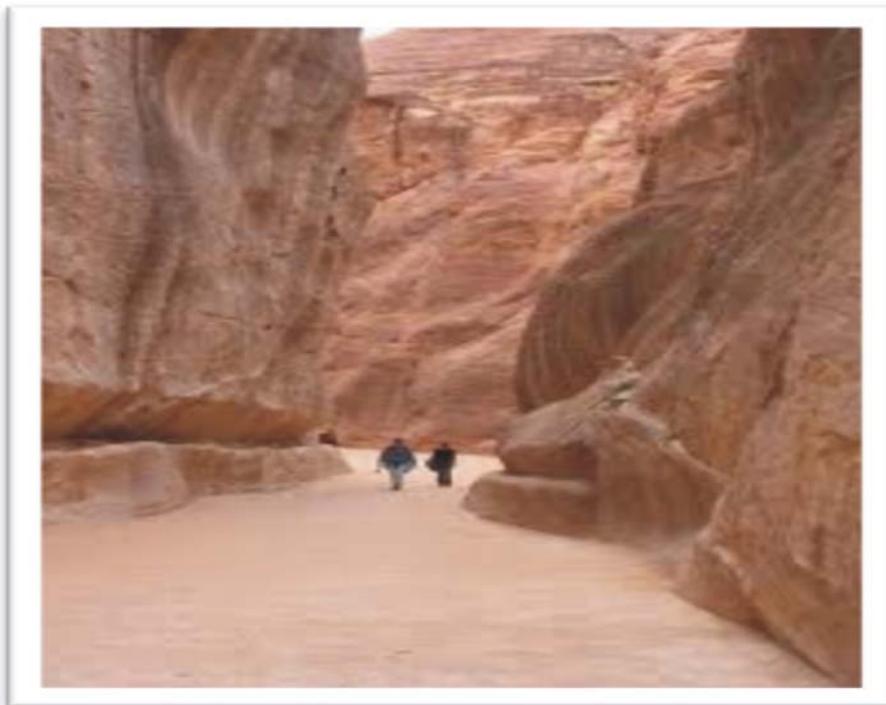


Fig. 6: Bends of the Siq can be seen where the two persons are present.

The Umm Ishrin Formation consists of quartz sandstone cemented mostly by iron oxides. However, the formation is not well cemented. It is rather relatively soft to carve, but not so friable as to fall down easily. This is possibly one of the reasons why the Nabataeans selected the Umm Ishrin Formation as a settlement site (Makhlouf, and Abed, 1991; Amireh, 1987). This phenomenon facilitates the process of erosion by flood water. Furthermore, and because of the relatively soft cement, the falling blocks disintegrate into loose sand and do not remain as blocks or boulders (Fig. 7a and b). This same phenomenon can be seen in the Wadi Rum area where no boulders or blocks are present at the foot of the mountains and loose sand dominates. On the other hand, the Umm Ishrin Formation is characterized by its long, vertical to near vertical joints. They can be seen in the same formation elsewhere in Jordan, as in Wadi Ram and the mouths of Wadi Mujib and Wadi Zarqa Ma'in (Abed, 2000).

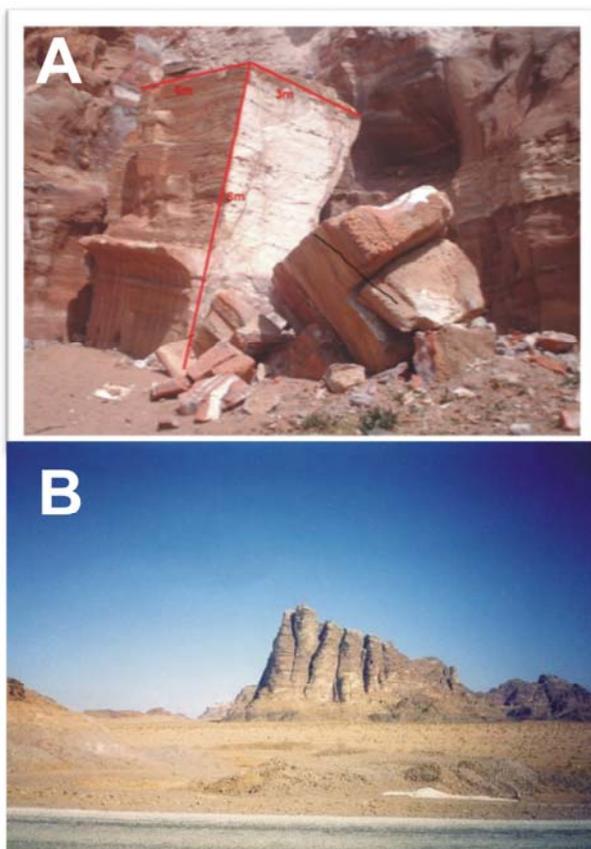


Fig. 7: The fate of falling rocks: A) A recent rock fall from the Umm Ishrin Formation in Petra. This block will disintegrate into loose sand within a relatively short period of time as is clear at the left, B) A field photo of the remnants (inselberg) of the Umm Ishrin Formation at the entrance of Wadi Ram. Note the non-presence of intact fallen rocks as all material has become loose sand. This property has facilitated the removal of eroded material with the passage of time from the Siq.

Some people believe that the Siq was all excavated by the Nabataeans; i.e. it is man-made. This is an exaggeration of their capacity and skills. The working hypothesis of this paper, which is to be proved in the following paragraphs, is that the Siq is natural and has nothing to do with the Nabataeans. It was present before they settled in Petra and made it their capital. The hypothesis is that the flood water of Wadi Musa acted on two joint sets of the Umm Ishrin Formation to erode and widen them in order to produce the present-day Siq. In other words, two natural processes were responsible for the formation of the Siq: jointing and flood water erosion.

More than 1100 joints in the Siq and its surroundings were randomly selected and their trends were measured (Table 2). The readings were plotted in a rose diagram (Fig. 8). Fig. 8 clearly shows two major sets of trends dominating the measured joints: 1) a NE-SW trend ranging between 50-80 degrees and centered at 60-70 degrees, and 2) a NW-SE trend ranging between 130-160 degrees and centered at 140-150 degrees with a major class at 150-160. There is an angle of 100 degrees between the two joint sets.

Likewise, the trends of the Siq bends of Table 3 were plotted in a rose diagram (Fig 9). Again, two major trends are clearly seen: 1) a NE-SW trend centered at 60-70 degrees and 2) a NW-SE trend centered at 150-160 degrees. The two major trends of joints and bends are exactly the same. However, there is more scatter in the trends of the bends (Fig 9) compared with the trends of the joints. Most probably the scatter in the directions of the bends is due to the small statistical sample of the bends (38 bends) compared with the joint readings (>1100 joints).

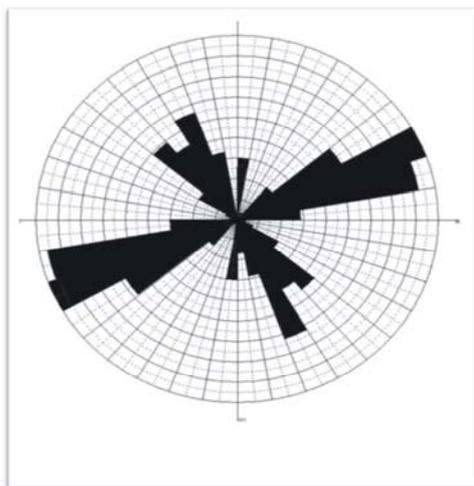


Fig. 8: A rose diagram representing 1136 joint trends in the Siq and its surroundings. Major trends are 60-70 and 150-160 degrees with other minor trends.

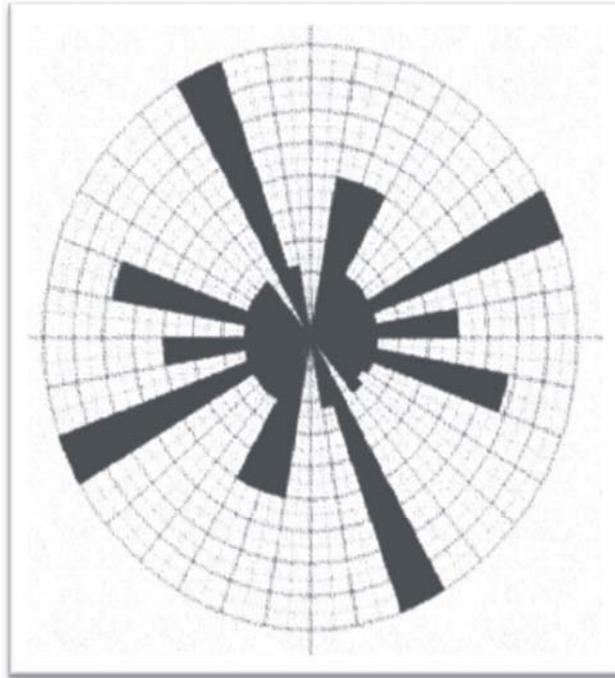


Fig. 9: A rose diagram representing 38 trends or directions of bends of the Siq. Major trends are 60-70 and 150-160 degrees with other minor trends.

The close similarity between the directions of the major trends of both the bends of the Siq and trends of the joints strongly suggest that the major trends of the joints were acted on by the flood water of Wadi Musa to form the Siq. This is a straight forward interpretation.

Wadi Musa is the main wadi in the Petra area that drains the highland east of Petra (Fig. 10) into the Siq then westwards to Wadi as-Siyyagh and further west to Wadi Araba. A meteorological station built in 1976 in Wadi Musa shows that average annual precipitation is 177 mm, with a minimum of 105 in 1987 and a maximum of 354 mm in 1988. The number of rainy days is 20.4 days per year. Rain is not uniform throughout the rainy months and most of the rain is either early or late in the season (Jordanian Meteorological Department, 2000; Farajat and Salameh, 2010). After rain, flood waters flow westwards and then change direction in the vicinity of the entrance of the Siq. The flow becomes from the NE to the SW where the flowing water meets the NE trend of the joints and starts eroding it. Then the whole process of erosion and transportation continues.

The Wadi Musa flood water first acted on the NE trending joints and continued

widening and deepening this trend until the erosion reached the NW joint trend, widening it and so on. When the base of the newly formed fissure is wide enough, the rocks above become hanging and they tumble as rock fall. The falling blocks disintegrate into loose sand, as discussed above in Fig. 7, which is carried away with the flood water, thus facilitating further erosion by the running water. The whole process of erosion, widening of the joints by flood water and falling blocks continued until the whole Siq was formed.

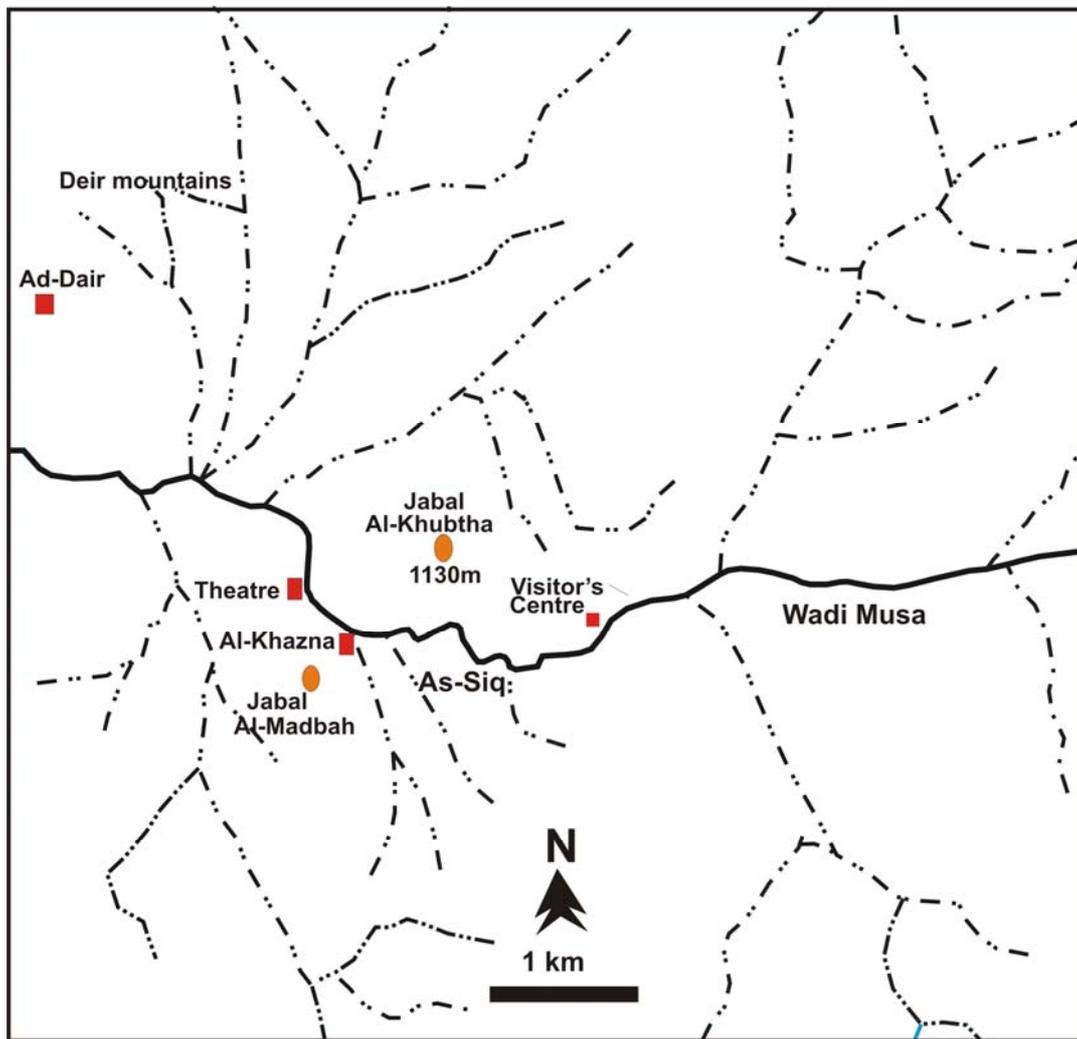


Fig. 10: Drainage system in the Petra-Wadi Musa area. Note that Wadi Musa drains all the area east of Bab as-Siq and the flow of Wadi Musa goes through the Siq westwards.

The formation of the Siq through the interaction between joints and flood water is time dependent, but time is always available for the working of geological processes. To start with joint formation, it seems reasonable to associate their formation with the major tectonic event of the Oligo-Miocene (35-20 Ma) which led to the formation of the Dead Sea Transform (Quennell, 1956, 1958; Barjous, 1987, 2003). Joints may have formed much earlier due to the northward movement of Arabia (and Africa) and the compression associated with that; e.g., the Syrian Arc Fold System of the Upper Cretaceous (Krenkel, 1924; Mikbel and Zacher, 1981; Bowen and Jux, 1987; Abed, 1989). Consequently, the Umm Ishrin Formation was already jointed millions of years before the subaerial exposure of the Petra area.

So, when did the upper surface of the Umm Ishrin Formation become exposed at the ground surface; i.e. subaerially exposed and ready for rain water erosion and formation of the Siq? The answer is rather complex and tentatively discussed here. The western mountain range in Jordan, including the Petra area, has been subjected to an ongoing epeirogenic uplift since the Late Eocene (Quennell, 1956, 1958; Powell, 1989b; Barjous and Mikbel, 1990; Abed, 2000; Barjous, 2003). This process is opposed by running water erosion which tends to lower the mountain relief. Water erosion is dependent on the relief as well as paleoclimate (Huckriede and Wiesemann, 1968; COHMAP Members, 1988; Abed and Yaghan, 2000; Abed et al., 2000). Higher rates of erosion are usually associated with higher relief. Erosion rates along the western flanks of the mountain range in Jordan are certainly faster than those of the eastern flanks due to differences in slope angle. Also, wetter plaeoclimates induce faster erosion compared with dry conditions. Due to the epeirogenic uplift, the highest peak near Petra (Al-Hisha) is around 1800 m above sea level (asl) before the removal by erosion of the Wadi Shallaleh Formation (Barjous, 2003). The floor of Wadi Musa near the entrance of the Siq is around 900 m (asl). That means that Wadi Musa has lowered its course 900 m in 36 Ma; i.e. towards the end of the Eocene. This simply means a uniform rate of erosion by Wadi Musa of around 0.025mm/year. Because the upper surface of the Umm Ishrin Formation at the entrance of the Siq is around 50 m above the floor of the Siq, then, the upper surface of the Umm Ishrin Formation was at the ground

surface around 2 Ma before present. In other words, the upper surface of the Umm Ishrin Formation, at the entrance of the Siq, was exposed to water erosion some 2 Ma before present. This is possibly a crude and an over-simplified exercise, but it is useful as a first approximation of the beginning of the formation of the Siq.

Conclusions

1. Ancient Petra was almost completely carved in the red, brown, violet and rose, fluvial quartz sandstone of the Umm Ishrin Formation of the Late Cambrian. Minor monuments are also present in the white massive quartz sandstone of the Disi Formation of the Early Ordovician. The whole length of the Siq is also present within the Umm Ishrin Formation.
2. More than 1100 joint trends were measured in the Siq and its surroundings, while 38 trends or directions of the bends of the Siq were also measured.
3. Rose diagrams show that the major trends of the measured joints and bends of the Siq coincide almost exactly at 60-70 and 150-160 degrees for both joints and bends of the Siq.
4. Wadi Musa flood water seems to have exploited the two major joint sets, eroded and enlarged them to form the Siq.
5. Most probably the Siq started forming some 2 Ma ago.

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