ARCHAEO-GEOLOGY IN PETRA, JORDAN

by
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Abstract

Geological aspects of buildings of the ancient city of Petra not only reveal a high level of engineering skills of the builders, but also a considerable practical understanding of geology. Carving of tombs, and building of temples and vital infrastructure was well adapted to the constant seismic threat of the site,(1)by favoring cliff carvings over free standing structures, (2) by sensible choice of building plots and in part(3) by mechanical cushioning of buildings. Measures were also taken to minimize damage to buildings by weathering and desert flash floods. Preservation, size and ornamental luxury of the tombs correlate with rock properties, and thus, with geology. The blocks used in some of the buildings and for paving can be traced back to distinct quarry sites from specific sandstone members. Quarries were operated using a range of techniques adapted to the local topography. Additional material seems to be quarried from the city center itself, thus leveling the site for further development.

Introduction

Reading the historic record of life in the ancient city of Petra is one of the most exciting things to do. But the reading should be from the remains at the site rather than from script.

It is mainly through a number of archaeological studies and excavations that we learned about Nabataean life and times in extraordinary detail (The Department of Antiquities of Jordan; The University of Jordan, Amman; Conway; Hammond; Joukowsky; ‘Amr; Kirkbride; Lindner; Parr; Stucky; Zayadine; to name but a few excavators).

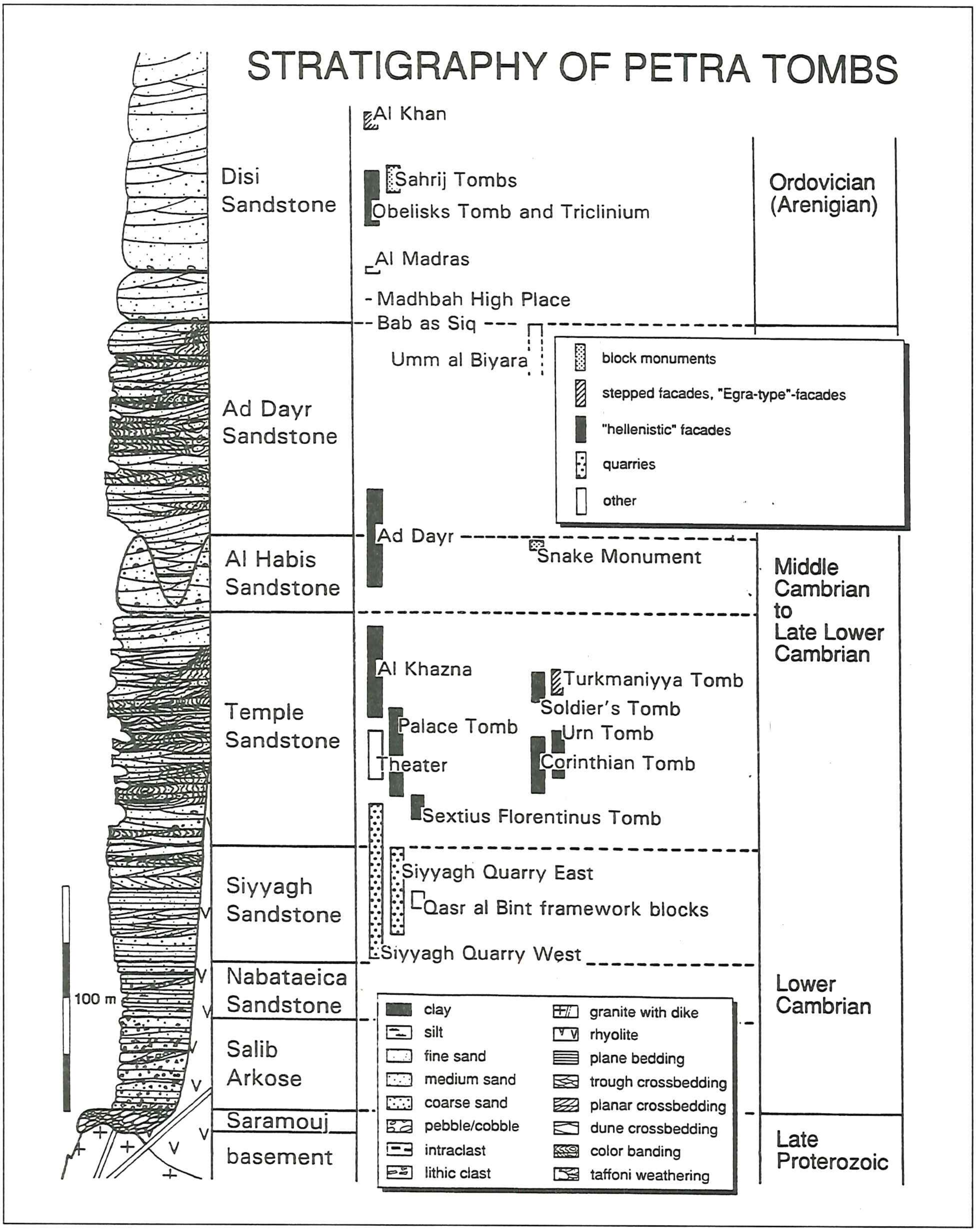
This history is a sequence of natural disasters, wars, and other stately affairs, as well as a record of religious culture, trade links, manufacturing and everyday life, all read from a succession of sediments and keystone artifacts and their relationship to the remnants of buildings.

This is in stark contrast to the mighty tomb façades that attract an ever-increasing number of admirers to the city: well preserved as they are, the historical information to be obtained from them is comparably limited to insecure dating via a stylistic analysis of the decor (e.g. McKenzie 1990) and a functional assessment of the floor plan of the rock chambers.

The historical record of the façades, however, is twofold and an interdisciplinary approach using both the archaeological as well as the geological record does add a variety of new aspects to our understanding of Petra. Admittedly, the two time scales involved differ by several orders of magnitude, but the combined reading of both records reveals some interesting detail about the making of, and life among, the monuments the Nabataeans have left to admire.

The database for the study is (1) a detailed stratigraphy of the early Paleozoic sandstones exposed (Fig.1) and (2) the projection of this stratigraphy into a geological map of the urban area of Petra (Pflüger 1990; the stratigraphic resolution of the geological map recently published by the Ministry of Energy and Mineral Resources, ‘Ammān, is not sufficient for this kind of study).

Building blocks now can be traced back to their stratigraphic origin, in some cases even to distinct quarry sites; the choice of



1. Stratigraphy and weathering profile of Cambrian and Ordovician sandstones exposed in Petra, Jordan. Lithologies and sedimentary structures of rocks are listed in bottom inset. Note that due to channeling-down of the overlying ad-Dayr member, the al-Ḥabis member is not present in some locations, e.g. the ad-Dayr plateau. The stratigraphic positions of tombs and other buildings of Petra are plotted in the centre column, distinguishing major building types.

some construction plots is found to be geologically sensible; the engineering of large buildings (and even more so the use of carved tombs) seems well adapted to a whole range of climatic and geological hazards, which were not considered in residential buildings (Kolb and Stucky 1993); the rock quality of cliffs correlates with the prestige of the façades they bear, and finally, there is reason to assume that not only some cliffs, but the whole topography of the city was shaped under the hands of Nabataean engineers to suit the needs and aesthetic preferences of a growing community.

Tectonics and Building Style

When we talk about engineering geology it must be noted that the Nabataeans avoided foundation problems (Hammond 1973: 77). The majority of the buildings is carved directly into steep, massive sandstone cliffs, among them the biggest and most elaborate. Assuming that they were aware of the seismic threat – Hammond (1986: 16, 22), Scheck (1987), Kolb and Stucky (1993) and Ambraseys *et al.* (1994) mention that major earthquakes devastated Petra in 363 (365), 551 and 747 AD – this may be one of the reasons why the Nabataeans chose the extraordinary architectural style of cliff-carving in the first place. This applies not only to the fronts of the tombs, such as al-Khazna and ad-Dayr, but also to the auditorium of the Theatre and especially to the vital municipal system of irrigation canals. The most amazing example leads from Wādī Mūsā all around the northern rim of Jabal al Khubtha to the Palace Tomb, in parts 25 m up the rock face. Laying a string of earthenware pipes in the ground would doubtlessly have been much easier, quicker and cheaper. We know that Petraean hydraulic engineers were familiar with the use of pressure pipes (Browning 1980: 48 and Fig.14), but as modern experience with underground pipes and cables in this flood-stricken area taught us, those hidden, fragile constructions are almost impossible to maintain (personal Communication Muhammad M. Khadija).

Foundations and Statics

As we are fortunate to know from an ever-increasing number of excavations, the ancient municipality did consist of more but carved tombs and cisterns. occupation layers in the az-Zanṭūr excavation (Kolb and Stucky 1993) record a trend from tent-dominated dwelling in nomadic and early Nabataean times to a larger proportion of stone-built housing in the later Nabataean and Roman periods.

The foundations of the "conventional" masonry buildings of Nabataean origin are rarely in valley alluvium, but mostly cut into compact bedrock devoid of siltstone bands. The Temple of the Winged Lions (Hammond 1986) and Qaṣr al-Bint (Wright 1961) may serve as examples for sophisticated foundations; their reasonably good state of preservation attests for (1) knowledge about the seismic threat of the area, and (2) a high level of "soil mechanics", building foundation and statics applied by their ancient constructors.

The story differs somewhat in more common housing objects like the Nabataean and Late Roman house at az-Zanṭūr given a trend of moving wall foundations from statically exposed positions near terrace margins (which is not a problem for tent pegs) towards the more stable terrace center. The housebuilders and owners mostly failed to go further and take more effective precautionary steps against collapse (not unlike the carelessness with which we build houses in our contemporary earthquake areas).

This is why, as after any major earthquake of today, common housing lies badly in ruins at Petra, and is one of the reasons for our difficulties in reconstructing the residential areas. This is all the more astonishing since we know that like today, measures to make buildings earthquake-proof were known, as shown by the cyclopic masonry of Qaṣr al-Bint, as well as by the cushioning and tensile reinforcement of the structure with interbedded layers of oak beams and stone blocks (Wright 1961; Zayadine 1986: 238; Bardorf 1988: 374). Common architecture of most times is not influenced by such knowledge.

Supplies and Commodities

The skill of the Nabataeans in water engineering (which resounds in the very name of the people, Negev 1976), was famed already in the ancient world (Scheck 1987: 345). In fact, parts of their irrigation system can still be used (Hammond 1973: 72), as for instance the dam (reconstructed in 1964, after a devastating flood disaster in Wādī as- Sīq had taken a heavy toll), the tunnel (al-Mudhlim) at Bāb as-Sīq and numerous cisterns. One of the largest cisterns near Sīq al-Bārid some 5 km north of Petra has recently been restored and now supplies several Bedouin families living in the al-Baydā area.

The importance of the tectonic setting for the sepulchral architecture of the city has already been mentioned; yet authors did not reach a consensus about where the population, estimated at about 10000, actually lived. Browning (1980: 48) even assumes a number of 18000 or 20000 inhabitants within the city area, plus some 10000 in the suburbs. Assuming that many families had a herd of goats, poultry and donkeys or camels, it becomes clear that only a part of the Petraeans could be accommodated in stone houses. Caves, on the other hand, were used as dwellings only from late Roman times onward (Zayadine 1974). Hammond's (1973) suggestion that the residential areas consisted of a combination of stone-, adobe- and wooden houses seems reasonable, but there is one caveat. Evidence for the use of adobe has not been found, and it is to be doubted even there was enough clay for building. Zayadine (1986: 260) found a clay source ('Ayn aṭ-Ṭīnah = source of the clay) near the road to the Umm Ṣayḥūn settlement that was just about sufficient for the unique, eggshell-thin earthenware to be produced there.

The sandstone province itself supplies only a few hard clayey silt bands and these would be unsuitable to produce terra cotta. Transport of clay on camelback from the Wādī 'Arabah or some place up the ash-Sharāh mountains may have been feasible for the production of luxury ware in manufactories of the central valley, but certainly not for adobe bricks, even if a minor quality of clay would do. Building materials locally available were sandstone, strips of woven goat hair still used in traditional Bedouin tents, and possibly more timber than can be found today. Even with an increasing number of common houses emerging from excavations, it is possible that even during the "glorious period" (second century BC to second century AD) a majority of the inhabitants in the suburbs lived in tents (cf. Negev 1976: 49). This is also in agreement with results from recent excavations (cf. Stucky 1990).

Weathering and Chronology

Due to the scarcity of inscriptions and artifact finds relating to the carving of the tomb façades, we are largely limited to an analysis of the decor when trying to date them. Given the difficulties with establishing a conclusive sequence of the carving of the façades it seems straightforward to use their variable degree of weathering to produce at least a relative sequence. This approach is hindered by the range of rock types chosen for the buildings. As shown in

Fig.1, monuments were carved into –

1. well-sorted Lower Cambrian Ṣiyyagh Sandstone which formed in a mature alluvial braidplain setting, rivers moving south to north,
2. multicolored Lower to Middle Cambrian Temple Sandstone formed on a somewhat more rapidly subsiding alluvial braidplain,
3. the light-colored, rarely yellowish, al-Ḥābīs Sandstone with conspicuous large-scale eolian dune cross-bedding,
4. fine-grained, mature alluvial braidplain ad-Dayr Sandstone, often with dark brown diffusion bands of Fe-Mn oxides that tend to resist weathering, and
5. almost white-colored Ordovician ad-Dīsī Sandstone, mainly of eolian dune origin.

In composition rocks range from fine-grained, highly compacted sandstones mineralized by carbonatic, kaolinitic or quartzose cements to coarse-grained and loosely packed, porous sandstones that are bound only by clay minerals and iron oxides (Amireh 1987: 127). Abu Safat (1986) has pointed out, how dissolution and precipitation within the pore space of the sandstone (depending on climatical and microclimatical factors) dictate the pathways of rock destruction: cement decomposition causing formation of calcareous crusts, exfoliation, and blasting of taffonis, or leading to general disintegration. This is why resistance to weathering is highly variable between these sandstone members.

Unfortunately the sandstones in which the well-known and decorative Liesegang color bands (mentioned already by early travellers like Russegger, 1847) are most beautifully developed are also the most porous and least durable ones; within these, weathering by combined action of both water and wind can easily be observed on a human time scale. Buildings using such banded rock, which mostly belongs to the Temple Sandstone member (Pflüger 1990), are subject to extreme rates of erosion, whether carved into a cliff or built from ashlars. Similar rates of rock decomposition affect the coarse-grained, light tan-colored al-Ḥabīs and ad-Dīsī Sandstone members.

Nevertheless, cliffs of these rock types are situated in the most prominent localities near the city center, are most colorful, and also most easy to work – a multitude, if not the majority, of façades is carved from these rocks in the Outer Sīq, the upper Wādī aṣ-Ṣiyyagh, in the al-Mu‘aysra and al-Ḥabīs neighborhoods, and also along the western scarp of Jabal al-Khubtha, referred to as the "King's Wall". Many of these tombs belong to the "arch", "pylon", "stepped", or "Hegr" ("Egra", Negev 1976) type, and must have turned out to disintegrate at an alarming speed soon after completion. Today many of them look more like natural taffonis and caves rather than man-made structures.

Other tombs were carved into the more rigid parts of the sequence. al-Khazna is situated in the more durable, but less colorful upper part of the Temple Sandstone, whereas the builders of ad-Dayr chose the lowermost portion of the ad-Dayr member (which is almost devoid of dark Liesegang bands at this location). While al-Khazna also benefits from its protected location in the narrow gorge of the Sīq, these tombs are in better condition mainly because of the choice of sandstone they are carved into.

The distance of ad-Dayr from downtown Petra beautifully illustrates a great dilemma, that the early builders were well aware of: there were a large number of cliff plots available in prominent locations, but only a handful of the them were in durable sandstone sequences. Nowhere is this problem more clearly displayed than in the row of large "hellenizing" monuments of the "King's Wall" (Palace Tomb, Corinthian Tomb and Urn Tomb). Cutting them out of crumbly but marvelously banded stone in

Petra's most prominent prospect, the Nabataean (or Nabataean-hired) masons of the first century AD took several extra measures to protect the monuments from sandstorms and wetness. Already sheltered between wind walls, the Palace Tomb was additionally protected by a broad platform more than three meters high (Browning 1980) that kept away saltating storm sand. Also torrents that occasionally streamed down Jabal al Khubtha and threatened the Corinthian Tomb were diverted to a vertical gully on the north side of the façade.

The Urn Tomb was set back in a deep excavation behind the rock face, on the one hand to gain space for a presentable forecourt (with a formidable view over the city) and on the other hand to remove it from the front of sandblasting by desert winds. Nevertheless, in the case of the two former tombs, the ingenious efforts obviously failed since the façades have through the millennia suffered horribly at the hands of the elements. For our modern hydrologic understanding it would have probably been most effective to isolate the façades from pore water seeping in from behind (instead of surface-coating, which only accelerates the crust-taffoni cycle of Abu Safat, 1987); today we may have that knowledge, but only the ancient Nabataeans could have afforded such an expense.

Another link can be observed between preservation of the monuments and the slope gradient of the rock they were carved in. Tombs or temples cut in gentle slopes required a tremendous mass of rock to be removed to obtain a vertical surface high enough for the topmost tip of the front decoration. Disregarding the expenses, this strategy had the advantage that the monument itself arose from fresh material several meters below the leached and weathered rock surface. Urn Tomb is a beautiful example – an additional explanation for the relatively fresh appearance of its lower parts. In contrast, in the shallow, near-vertical sections of the rock used for example in al-Ḥabīs and the "King's Wall" the porous cement had already been leached and incrustation taken place prior to the carving.

For the Nabataeans, however, setting back façades behind the rock face had also a serious disadvantage: Liesegang color banding was not predictable any more. Even if some of the chambers had been originally decorated by frescoes and molding, like the famous biclinium in the Sīq al Bārid, the Unayshu Tomb, or the cave high above the Wādī aṣ-Ṣiyyagh (Zayadine 1986: Fig. 49), the natural banding of the Petraean sandstone arguably remained the preferred decor. Many of the major tombs simply cannot be imagined without it, and the effect must have been intended. After all, the Nabataeans honored Dhushara, their highest deity, in the form of a stone, and using the beauty of the rocks for sacred buildings seems to be a natural kind of worship. Examples are numerous, the multi-colored triclinium hall opposite to the Tomb of the Roman Soldier, Silk Tomb and Palace Tomb to name the most famous.

Here the struggle for an aesthetic expression is apparent. Thus the question arises why the architects of al-Khazna and ad-Dayr, the uni-colored counter examples, did without this stylistic device - probably the uniqueness of the building sites and the rock quality offset all other considerations. It is also possible that due to a new stylistic development the irregular patterns were felt to distract from the strict symmetry of the architecture. However, many authors favor the idea that these two, or even most of the tomb façades were originally covered by a thin veneer of white stucco which produced a marble-like sheen (e.g. Fellmann, Brogli and Stucky 1993). Whatever proves to be true, there is good reason to assume that the Nabataeans well understood the connection between color banding, strength and weathering of their stone.

For all the damage weathering does to the unique architecture at Petra, it is in our hands to make use of the very process of weathering: taking together all knowledge about the lateral and vertical changes of properties of the sandstone, the hydrological setting of the area, the climate and especially, the microclimate of façades in different locations and orientations, we should be able to assign a unique number on a scale of relative proneness to weathering to each building site. If the degree of weathering of each façade is then assigned a unique number too (e.g. by roundness-measurements of edges that originally had a sharp right angle, as commonly done in sedimentology), both scales can be overlaid to produce a relative time sequence of the cliff carvings, with the few unequivocal dates known from inscriptions (e.g. Tomb of Sextius Florentinus, 129 AD) used for calibration.

Weathering and Prosperity

Comparing the sizes and decorations of buildings that can unequivocally be identified as tombs (burial niches in the stone chamber and/or urn niches in the façade) with their states of preservation and stone type respectively, there seems to be an overall trend that the larger and the more flamboyant the tombs, the better is their present condition. All of the well-known façades can be named as examples, with the exceptions of the King's Wall just mentioned.

In contrast, the vast majority of smaller and less adorned tomb fronts were chiselled out of stone of minor quality and with less sophisticated precautionary measures against dilapidation. After all, the "Swiss cheese" look of al-Ḥabīs, al-Mu'ayṣra, the western Jabal al-Madhbaḥ and other districts of the city stems from the rapid decay of hundreds of small tombs. Some of them have even been built across major siltstone bands (just as the Theatre) and are now completely dissected by wind corrasion of the soft sediment bed. All this leads to the conclusion that the higher in rank and fortune a person was, the more durable a tomb the person could afford with respect to both type of construction and geological setting.

It is an interesting idea that there may have been an authority to assign plots fitting the status of the customer. There must have been restrictions or laws controlling building, or else the immediate vicinity of extravagant shrines like al-Khazna would have been scarred by smaller, "common people's" tombs, trying to profit from the prestige of their neighborhood. This, however, is rarely the case. Different parts of the city are characterized by sequences of tombs standardized to a degree that reflects reglementation as more likely than personal taste. The environs of the Theatre and the suburbs of Mughur an-Naṣarā and al-Mu'ayṣra, for instance, show tombs carved in the same general style and similar dimensions. Since the whole place was densely populated, and room for new tomb façades eventually became limited, we may safely assume that realty prices not only depended on the distance from the center and distinction of the site, but depended on the geological qualities of the site as well, as outlined above. After all, Petra was one of the financial centers of the Middle East (Negev, in contradiction, claimed that "Petra was economically unimportant", 1976: p.XIV), with all the prestige and property speculation of a modern trade place like Amman, London, New York or Tokyo.

Building stones

aṣ-Ṣiyyagh Sandstone

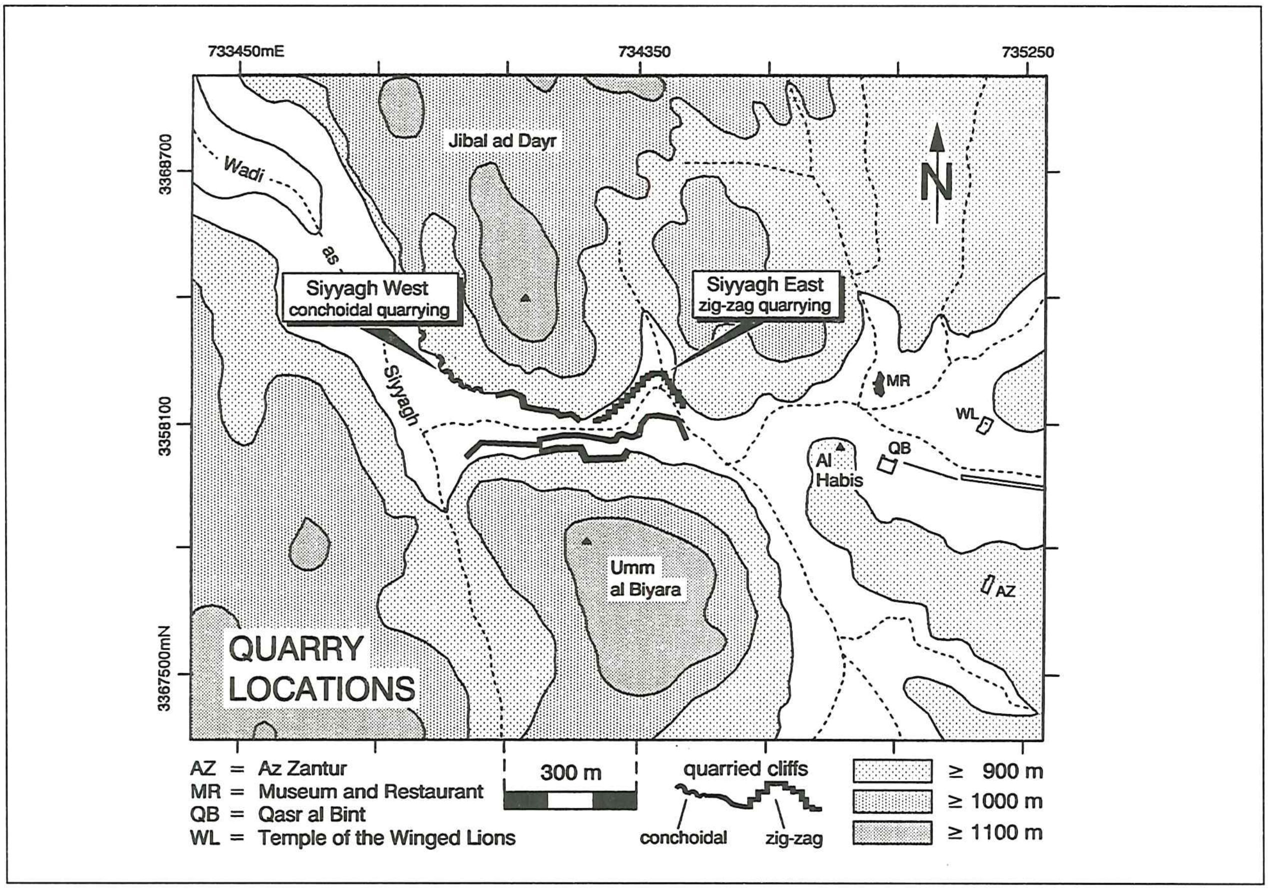
While establishing a lithostratigraphic subdivision in the Cambro-Ordovician sandstone sequence, information about the provenance of the building stones used in

Petra was gained as a by-product. In selecting stones for whatever purpose, Nabataeans had to consider (1) transport distance, (2) efforts required to quarry and dress the stone and (3) the quantity of stone available. The size of the blocks demanded by the architect and the skill of moving them in the given landscape usually also limited the selection.

Using a variety of petrological and sedimentary characteristics (Pflüger 1990), the fine- to medium-grained yellowish rose colored sandstone used in building Qaṣr-al Bint (aṣ-Ṣiyyagh Sandstone) can be traced to the quarries down Wādī aṣ-Ṣiyyagh. Indicators for this material are the fine to medium grain size, the predominance of tabular-planar crossbedding, the high resistance to weathering, the dark rose-brown color of the fresh stone and the light yellowish rose color on bleached surfaces, the lack of distinct Liesegang banding and the massive rather than bedded texture.

This provenance is not surprising, since Wādī aṣ-Ṣiyyagh preserves the only quarries of the aṣ-Ṣiyyagh Sandstone in question (with the exception of a smoothed-out portion in the northwest face of an Nijr 30 to 50 m up from the valley floor, just east of the High Place stairway, (Pflüger 1990: Pl.I). Besides, the size of blocks sketched by the quarrymen in bedrock of the quarry overlooking, and northeast of, the confluence of Wādī aṣ-Ṣiyyagh and Wādī Umm al-Biyāra (quarry Ṣiyyagh West in the following, Fig. 2) corresponds to the standard size of wall stones in the temple.

Only in the base of the temple, intensively colored orthostat blocks of Temple Sandstone were inserted, but in this case not for



2. Quarrying for building blocks of high quality occurred exclusively in the lower part of Wādī aṣ-Ṣiyyagh from outcrops of the sandstone member of the same name. Quarries of the Zig-Zag and conchoidal type are marked in the map, while smooth vertical quarries are shown in heavy black lines.

reasons of decoration, as the walls were originally covered by delicate ornamental plasterwork (Zayadine 1986). In contradiction to Browning (1980: 168) the Wādī aṣ-Ṣiyyagh quarries are probably sufficient to account for the provenance of building stones of a substantial part of the city's buildings.

As can be estimated by extrapolating natural rock slopes in the narrow Ṣiyyagh gorge, the volume of rock quarried there was limited, as is the number of building blocks in the rubble of the ancient city made from aṣ-Ṣiyyagh Sandstone (as noted further down, quarrying was also limited to the time before the Colonnaded Street was built). This choice building material was expensive because (1) it was harder, (2) it was more difficult to quarry especially from near-vertical cliffs of the Ṣiyyagh West quarries that might have required expensive wooden scaffolding (see also Quarries and Aesthetics, below), and (3) because an arduous cart transport through the unpaved Wādī aṣ-Ṣiyyagh added a premium on the price.

The Temple Sandstone

As already mentioned, the quarries in Wādī aṣ-Ṣiyyagh were insufficient as a source for all the temples and secular buildings that still stand or lie in ruins. This is even more true if older ruins buried under the younger ones are taken into account. Given the six- or seven hundred years of Nabataean culture, a flourishing industry and commerce even after the Roman occupation, a high frequency of wars and, occasionally, severe earthquakes, there must be several layers of ancient civilization still hidden in the ground. Fifteen of them have been identified by Hadidi (1986: 11).

Since rapid decomposition of the rock itself limited the recycling of old masonry, the total building material used mounts up to an immense volume. A closer examination of the ashlars scattered over the hills of the central valley shows that a large portion belongs to the medium to coarse-grained, most beautifully colored, but poorly cemented and thus most perishable sandstone member, the Temple Sandstone (Fig. 1). On the other hand, today's landscape lacks the scars expected after centuries of extensive quarrying of this unit which crops out mainly in the central valley. This is why stones must have been broken either from shallow pits within the city, or were produced by levelling a number of smaller Temple Sandstone inselbergs that very likely rose within the urban basin-to-be.

Additional material came from preparatory excavations of new tomb sites in gentle slope areas mentioned earlier, from the excavation of burial chambers like the one inside Urn Tomb, and from cavities like the Theatre. This would have kept transport distances within limits, and at the same time levelled the valley and extended the site for further dwellings. In this way human activity may even be involved in the smooth, hilly topography of the once inhabited quarters of Petra, a morphology which is rather untypical of the mountainous sandstone province of Edom.

Silicified Limestone

A third type of building stone was introduced for road construction and for pavement of the main roads. Flagstones, trimmed to rectangular, flat shapes and recognized as limestone without exception (e.g. Scheck 1987: 366) formed the original pavements along the Wādī as-Sīq and in the magnificent avenue ("Marble Road") that connected the two centers of Petra – al-Ḥabīs, i.e. the sacral temple precinct with Qaṣr al-Bint, and the theatre area as the social center in the view of many authors.

The clean, light brown to whitish, shelly and partly silicified calcirudite belongs to the Silicified Limestone unit of Bender (e.g.

1968a) and is Cretaceous in age. It forms the crest of ash-Sharāh mountain chain and crops out in the topmost parts of the modern town of Wādī Mūsā. The silicified limestone blocks provided by natural erosion and landslides are extremely resistant to weathering and mechanical wear, so much so that the bedload of Wādī Mūsā consists almost entirely of boulders of this type. Before the Bāb as-Sīq dam was built, ephemeral winter floods brought paving-size raw material right into the city.

The equilibrium amount of blocks present along the Wādī since prehistoric times may well have been sufficient for the pavement. Sparing the efforts of quarrying and transport, such blocks very likely were picked out of the stream bed, for example downstream from the present-day "horse park" at the Bāb as-Sīq, or in downtown Petra where the narrow ravine of the Outer Sīq once debouched into the central valley and dropped its freight. As an exception, the procession road west of the Triumphal Arch (Temenos Gate), was carried out with soft Temple Sandstone – either for aesthetic reasons, or because the comfortable sources of lime flagstones had been depleted (as ancient quarries were never found in the silicified limestone member).

A final observational detail in the paving is that both the sandstone part of the road west, as well as the hard limestone pavement east of the gate, lack the wear marks of cartwheels that are so common on Roman roads – this part of the city probably was proclaimed a pedestrian zone. This is likely to indicate that by the time the road was built (terminus post quem 9 BC or 76 AD, McKenzie 1990; 9 BC - 40 AD, pers. com. Muhammad M. Khadija), quarrying and transport of blocks from aṣ-Ṣiyyagh quarries had already come to an end.

A thousand years later the Crusaders with their emphasis on the strategic function of buildings gave up to be choosy about building stones. So the remnants of the walls of the al-Ḥabīs fortress are scattered with limestone ashlars in a framework of sandstone blocks of diverse provenance. Some of them are diagonally hatched in the typical Nabataean way – evidence that Crusaders did not mind to quarry older buildings. Not even the most elaborate monuments were safe from being recycled by the newcomers, when they hurriedly constructed their defense belt of "Oultrejourdain".

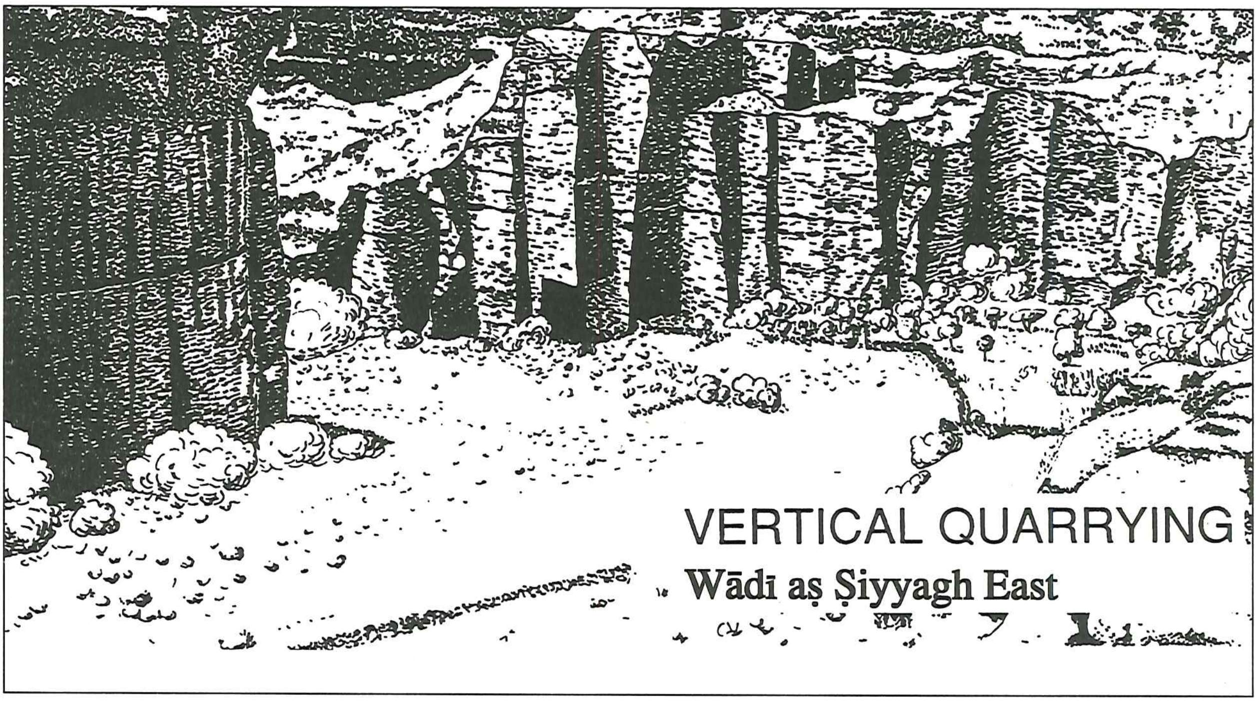
A few blocks with one or two sides perfectly even and smoothed out were found on al-Ḥabīs and possibly stem from the Qaṣr al-Bint, which must have already been partly collapsed by that time, and was the source closest to the medieval construction site of the Franks.

Quarries and Aesthetics

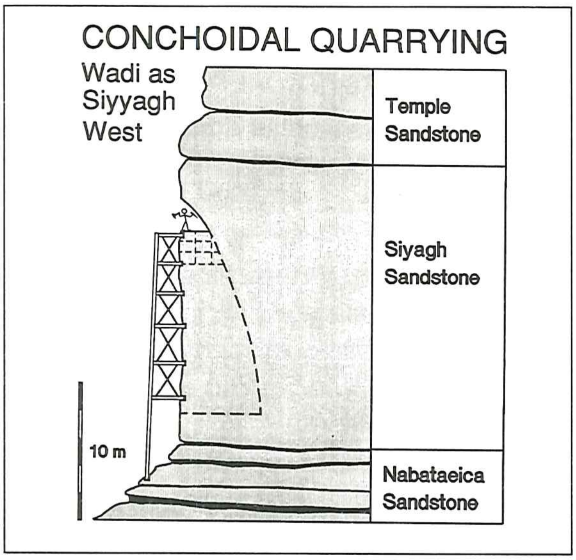
To the traveller of the late 20th century just as to early inhabitants of the city, the magic of Petra is embodied in cliffs. It is upon entering Bāb as-Sīq that multicolored cliffs rise sky-high, while the path is nothing but a crevasse ruptured open by tectonic unrest along the Jordan rift, engraved by sand storms and flash floods. Then it is the perfect harmony and impeccable detail of al-Khazna, a rose cliff shaped by the hands of humans, which has the observer gasping. And passing the weathered tombs of the Outer Sīq, the busily built-up cliff of the Theatre Necropolis, and the mighty King's Wall, it appears that it is the contrast of perfectly carved versus naturally weathered cliffs, which adds profusely to the charm of the place. And there is a third type of cliff, overlooked by most visitors, which in any other place would be considered just the opposite of decorative, yet, the ancient quarry walls in the Nubian Sandstone of Petra are aesthetic.

The new "Tourist Map of Petra" (Royal Jordanian Geographic Centre 1992) shows aṣ-Ṣiyyagh East quarry (labelled "Old Quarry") about 500 m downstream from the Petra Museum, but cliffs along almost the whole stretch of the Wādī aṣ-Ṣiyyagh between the quarries Ṣiyyagh East and West show the toolmarks of Nabataean stonemasons. Rock production left the cliffs dressed in three general shapes:

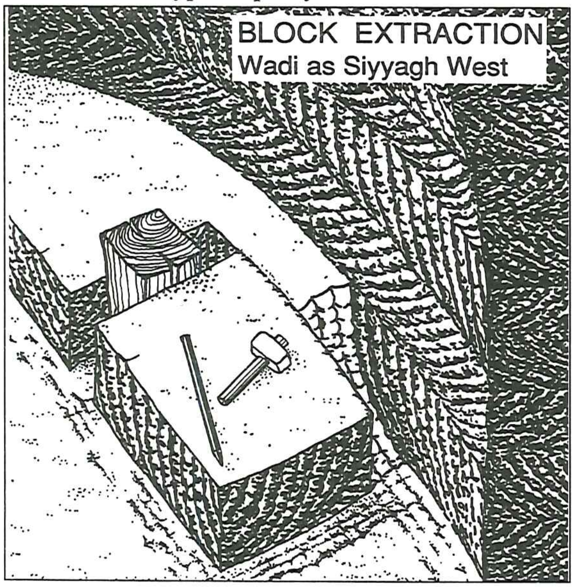
1. *Vertical "Zig-Zag quarrying"* (McKenzie 1990) is used in cases where the initial slope gradient of the rock is less than about 45 degrees. This allows the working face to gradually move backwards as work progresses, until the face reaches a critical height (which for quarries of all three types in Petra is about 25 m). Further expansion is then done laterally rather than vertically. The best example for vertical zig-zag quarrying is the Ṣiyyagh East quarry shown in the centre of Fig. 3. The reason for using a zig-zag floor plan is that blocks are always extracted from the edges; since chiselling-out of blocks the Nabataean way (Fig. 5) was time-consuming, more edges provided more working places for quarrymen at a given time, conducive to a higher productivity (as applies also to the numerous Nubian Sandstone quarries of ancient Egypt described by Klemm and Klemm 1992). The conspicuous overhanging niche at the present-day bottom of the northwest side of the quarry (left of centre in Fig. 3) seems carved during late-stage extraction of an oversized block which could not be absailed down from the top.
2. *Smooth vertical quarrying* is shown on the left-hand side of Fig. 3, and extends along most of the south side of the lower Wādī aṣ-Ṣiyyagh between the east and the west quarries. It was used in locations where natural rock slopes were steeper or even vertical, and the volume of extractable rock was limited. As the time and effort involved is belittling the amount of quarried blocks, the clearing



3. Vertical quarrying, Wādī aṣ-Ṣiyyagh East quarry, looking northwest. The quarry in the background is carved into gentle rock slopes of the Ṣiyyagh Sandstone member at the foot of Jabal ad-Dayr. Conspicuous are its zig-zag floor plan as well as an overhanging block explained in the text. Vertical rows of notches (unfit for use as hand- or footholds) in some of the walls may indicate the use of wooden scaffolding. The smooth vertically-quarried cliff in the left foreground (northeast foot of Umm al-Biyāra, see also Fig. 2) did not produce a large volume of rock, and might have been smoothed for aesthetic or religious reasons.



4. Conchoidal quarrying in the vertical cliffs of the Wādī aṣ-Ṣiyyagh West quarry and its relation to the sandstone stratigraphy. Quarrying proceeded from top to bottom in the way indicated by the dashed lines – and mainly in the massive Ṣiyyagh Sandstone, while a few niches reach up into relatively massive portions of the overlying Temple Sandstone. Scaffolding may or may not have been used in this type of quarry.



5. The way Nabataean quarrymen isolated blocks can still be studied in the conchoidal niches of the Wādī aṣ-Ṣiyyagh West quarry. The trenches are 15 cm wide with usually four rows of chisel marks preserved at the bottom of trenches and in unfinished sites like the one sketched. After trenching of the vertical faces, blocks were horizontally sheared from the bottom, either by the watering of wooden wedges, or using a long lever. The tools are shown for scale only.

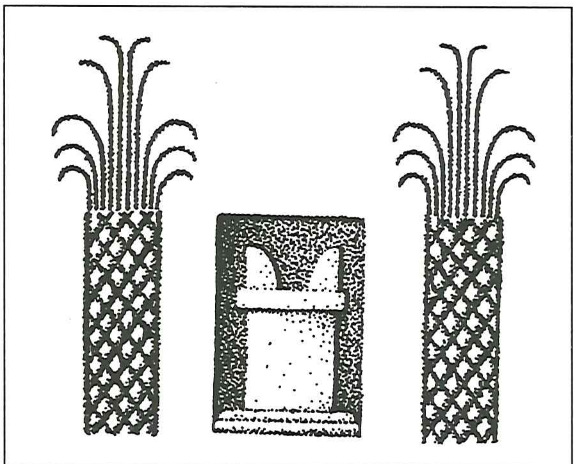
and smoothing-out of these cliffs may as well have served a different purpose than producing building blocks.

3. *Conchoidal quarrying* is unique to Petra. The conspicuous abris or niches comprise the bulk of aṣ-Ṣiyyagh West quarries, shown in schematic cross-section in Fig. 4. The purpose of these shallow conchoidal excavations (each 14 to 25 m high, around 20 m wide and a maximum of 8 m deep at the base, narrowing and shallowing towards the top) was to extract building blocks from the massive and high-quality aṣ-Ṣiyyagh Sandstone member exposed in the lowermost 35 m of the 250 m tall, near-vertical, southwest cliff of Jabal ad-Dayr. From the huge blocks which scatter the slope and Wādī bottom beneath the niches, we can read that the workers here had to deal with cliff failure and rock falls. The shape of the niches, however, is a fair compromise between the need to maximize production (and thus, undercutting), and keep destabilization of the vertical cliff at a tolerable level.

The procedure by which the quarrymen isolated the blocks with hammer and chisel on the four vertical sides before shearing them horizontally from the base (most likely by watering of wooden wedges, as illustrated schematically in Fig. 5, or by using leverage) can still be studied in the aṣ-Ṣiyyagh quarries. It left the quarry bottom fairly uneven, and cliffs diagonally hatched in the well-known herringbone pattern (which should not be confused with the delicate diagonal tooling used in very few instances for keying the stucco, for example in the chamber of the Urn Tomb or the Tomb of the Roman Soldier, McKenzie 1990: 33).

Several questions arise from this suite of quarries: What factor determined the critical height of the quarried cliffs? Was it restricted by the structural limits of wooden scaffolding, or was the transfer of blocks from higher-up unsafe? Why were the quarries abandoned by the time the Colonnaded Street was built? What was the reason for all that unprofitable smooth vertical (type-2) quarrying along the lower Wādī aṣ-Ṣiyyagh (as well as in numerous locations along the Sīq, the stairway to ad-Dayr, the Wādīs al-Farasā and an-Numayr, to name only a few)? If rock faces were smoothed without any practical necessity, they might have had a decorative purpose. Perhaps it was done in an act of worship of the Nabataean deity Dhushara, who was believed to dwell in the stone, as is strongly suggested by innumerable niches and nefesh adorning the gorges, and even more so by a number of altars that have even been carved into the walls of quarries-to-be-abandoned (Fig. 6).

It is with this speculation that I want to hand the subject back into the hands of professional archaeologists, who have already achieved so much to build our understanding of ancient life in one of the most fascinating places on Earth. I hope the present study managed to capture some detail that a geologically trained mind might add to the picture that slowly emerges from an ever-increasing treasure of wonderful studies on Petra. Many questions had to be left open, as many places remained unexplored.



6. Nabataean altar carved into conchoidal quarry niche, 10 m from bottom, Wādī aṣ-Ṣiyyagh West (3368250 m N 733880 m E). The carving is about 1m wide.

The strict limits of time and means left the resolution of some data quite unsatisfactory, but a closer look for instance at the rocks of the Temple of the Winged Lions, the Propylaea of Jabal al-Madhbaḥ, or the subconstructions of the Urn Tomb should be exceedingly interesting. The relative time sequence of the various buildings remains a mostly unsolved problem, but large parts of the valley still await excavation, and hopefully more studies will find adequate funding and get carried out – hopefully with archaeologists and geologists in a concerted effort.

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