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Historic Management of the Dynamic Landscape in the Surroundings of Petra, Jordan

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Abstract

Terracing and the construction of a flood control system in Petra has allowed a unique opportunity to examine landscape conditions and changes beginning with the Late Iron Age. The study area is the Hremiyyeh catchment that flows into the core of the archaeological city of Petra and therefore constitutes an important key to understanding the human settlement of the area. The location was chosen as a focal point for intensive investigation and the study of human response to environmental change. This study involved careful documentation of the topography, geology, and archaeology of the site. In addition, samples were taken for the dating of terrace construction and changes in the landscape. The study indicates that the hydrological interventions began in the Late Iron Age, and intensified during the Nabataean and Early Roman periods. At the time, some of the drainage areas were already deeply gullied, while other parts had recently accumulated sediments. The lower terraces became filled with water-logged sediments, leading to the deposition of carbonates. The upper terraces changed the drainage pattern and deposition of the sediments. The sediments trapped there seem to have been less water-logged. The abandonment of the system at the end of the Byzantine to Early Islamic periods led to partial collapses, gullying, and bedrock downcutting. Due to soil accumulation, the upper terraces were restored and enhanced with new ones around the 11th. Century CE, probably due to partial reclamation of the area by nomadic settlers, with charred botanical evidence found indicating the burning of wild vegetation in favor of domesticated cereal and legumes, with relatively humid conditions.

Keywords: *Petra; Jordan; Landscape evolution; Human Responses; climate*

1. Introduction

The area of Petra in southern Jordan (Figure 1) is a tectonically and climatically challenging place for a major urban and trade center. Specifically, the area is characterized by an arid climate, high relief, flash floods, and earthquakes. Despite this, the area has been well harnessed since the Edomite (Iron Age II) period onwards (Bienkowski, 2013), with the local environment providing water, food, and other necessities for human habitation with sufficient control of the natural hazards that characterize the dynamic landscape.

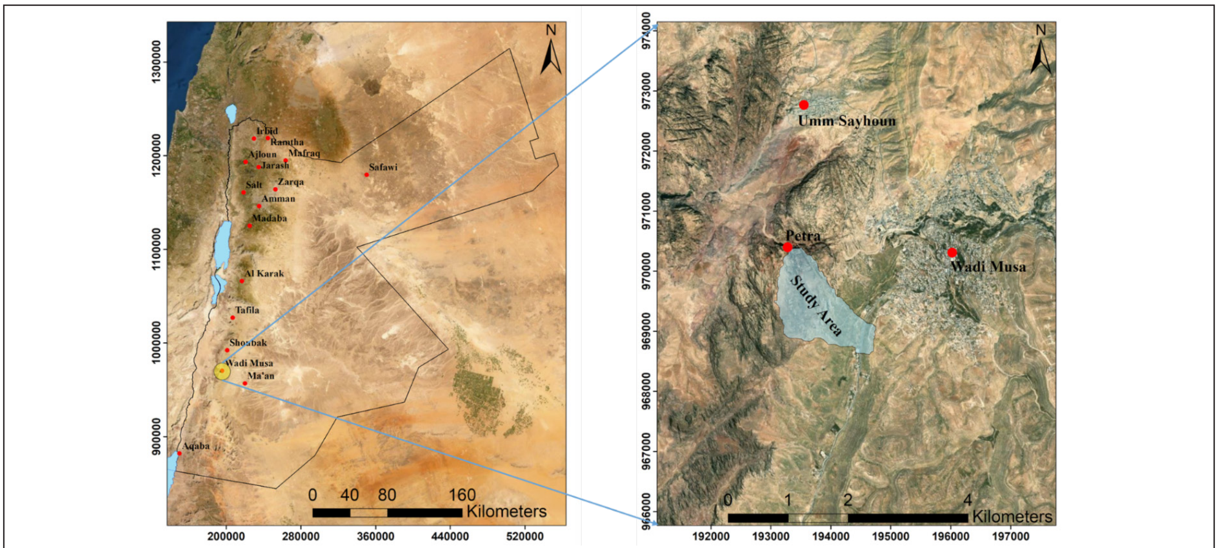

Figure 1. Location of the study area concerning Petra and Wadi Musa.

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Historic Petra has witnessed significant environmental changes over the last three millennia. Three factors have led to this change, i.e. climate fluctuations, tectonic movements, and anthropogenic interventions. These can be detected through the architectural landscape, where humans intervened by building water management and soil control features, better known as terraces. Terraces store climatic, topographic, and agricultural evidence through their very presence as well as in the sediments accumulated behind them. Moreover, they also provide potential clues to more sustainable management approaches for flood control, soil protection, and agriculture, even under different prevailing sociopolitical and economic conditions.

Recently, researchers have addressed various aspects of environmental change in the Petra area. It has been shown that a lacustrine environment prevailed in the area in the late Pleistocene and the early Holocene, and subsequent tectonism in the area changed the drainage pattern from a southerly direction to a westerly one (Abu-Jaber et al, 2020a). Hamarneh (2022) has surveyed the variety of terraces in Petra, discussing their ages, functions, and aspects of their environmental imperatives. Varieties in terrace function reflect site-specific priorities and included objectives such as flood control (Al Qudah et al., 2016; Abdelal et al., 2021), agriculture (Kouki, 2012), water collection, soil conservation and infrastructure protection (Hamarneh, 2022). Moreover, materials collected behind the terrace walls can contain important climatological materials that can help understand land-use practices in the past (Hamarneh, 2022, Bäumler, 2020).

The slopes and valleys around the ancient Nabataean city of Petra are heavily covered by terraces. These terraces were not constructed all at the same time but do reflect human response and adaptation to the concurring environmental events, mainly droughts, landslides, or floods.

1.1 Terraces as proxies for dynamicity:

Terraces are man-made dry walls constructed from natural stones without the use of any binding material to preserve and accumulate soil, mitigate flooding, and expand agrarian activities on steep slopes (Spencer and Hale, 1961; Treacy and Denevan, 1994). Terraces are sometimes built on bedrock, but more often they are built on accumulated soil or constructed to confine accumulated soil. In some areas, the soil was brought from other locations and dumped behind terrace walls. In such cases, the nature of the soil, and the dip of the accumulated layers can lead to the understanding of the history of the fill (Frederick and Krahtopoulou, 2000). Naturally accumulated soil fill might contain other evidence of practiced activities, surrounding ecology, and environmental conditions. Thus, part of the archival nature of terraces is encapsulated in the sediments and soils accumulated behind the terrace walls.

Terrace foundation elevations mark the location of the ground levels at the time of construction. And while the discussion may occur about how much change has occurred to the ground level behind the terrace wall (i.e. is the soil older than the terrace or not), the fronts of terraces certainly mark the ground levels at the time of construction. Thus, the down cutting of the stream level in front of the wall is clear evidence of the stream down cutting and back cutting that occurred since the structure was built. The ages of the sediments below, in front of and behind the terraces, differ, reflecting the sequence of events. While the soil behind the terraces remains sealed, with disturbances occurring only in the topsoil, the soil under the terrace riser remains sealed as long as the riser wall remains intact, unlike the soil in front of the riser which can be washed away, re-deposited, or cut into. Moreover, it is possible to determine the locations of terraces that have been destroyed using characteristic carbonate deposits that were left behind (Abu-Jaber et al., 2020b). Thus, it is possible to determine stream level elevation drops based on downcutting into these carbonates and underlying bedrock.

Terrace construction location, the longevity of exploitation, expansion, and abandonment patterns can be considered to be responses to prevailing conditions, especially when the study of these patterns is combined with analysis of accumulated sediments and their trapped paleoclimatic and paleoenvironmental proxies. Thus, even when another cultural material is lacking (such as monumental buildings), terraces can provide a wealth of evidence on prevailing conditions at the times of their building and exploitation. Furthermore, their sturdy and stable walls have made them ideal proxies in various parts of the world for studying the history of anthropogenic landscapes (Kiesow and Bork, 2017). And since these terraces in Petra extend in time from the Iron Age until now, much might be learned from studying them.

The evolution of human settlement patterns and changes in human daily activity were generally used as indicators of changes in climatic conditions. However, this is too simplified an explanation as socioeconomic and political factors influence human settlements (Jones et al., 2019). After undertaking an intensive survey in the area of Petra, the drainage basin of Hremiyyeh was selected for a detailed study (Figure 2). This includes the determination of the ages of human interventions in the area, changes in geomorphology as evidenced by carbonate deposits, down cutting, and terrace collapse, and changes in the vegetative cover through the study of plant remains (phytoliths). This study aims to show how a detailed examination of these terraces can increase understanding of their construction as responses to changes in environmental conditions through time.

1.2 The study area

Petra lies in the south of Jordan along the margin of the Dead Sea transform fault. The tectonism in the area affected a lithological sequence that spans from the Precambrian basement rock through the Late Cretaceous carbonate shallow marine platform rocks (Barjous, 2003). This tectonism began with epeirogenic uplift in the Late Eocene or Early Oligocene and continues throughout the Quaternary in the form of uplift, folding, faulting, and volcanism (Barjous and Mikbel, 1990). This now manifests in a series of sub-parallel normal faults and remnant rift basins that generally trend NNE-SSW. This is called the Quwayra Fault Zone (Barjous, 2003), and part of this zone includes the Wadi Musa fault.

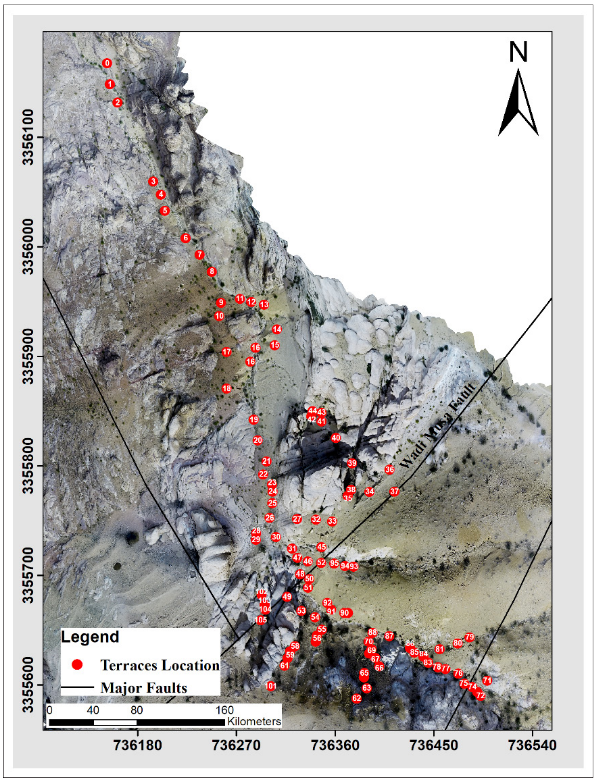

Figure 2. Wadi Hremiyyeh, showing the distribution of terraces, as well as the faults cutting through the area.

The drainage basin of Wadi Hremiyyeh, which was examined in this study, is on the eastern margin of the Dead Sea rift zone, with the Wadi Musa Fault cutting through it. The lower part of the drainage basin consists of Palaeozoic sandstone deposits (Red-varicolored Cambrian Umm Ishrin Sandstone overlain by white Ordovician Disi Sandstone; Barjous, 2003) and the Pleistocene lacustrine deposits in the lower (western) sections (Abu-Jaber et al., 2020a). Lower Cretaceous Kurnub Sandstone and Upper Cretaceous marine limestone and marl sequences crop out to the east of the fault (Figure 3). In addition, overlying undated Quaternary alluvium and colluviums are seen in the upper (eastern) sections (Barjous, 2003).

Thus, the Quaternary deposits include Pleistocene and Holocene colluvium, gravel, and soils on the slopes overlooking Petra (Barjous, 2003), as well as fluvio-lacustrine deposits within the main rift basin at the lower elevations below the 1060 masl contour line (Abu-Jaber et al., 2020a). Recent deposits also include a variety of terrestrial carbonates (Abu-Jaber et al., 2020b) and occasionally significant loess deposits, particularly related to abandoned archaeological sites (Lucke et al., 2019a,b).

The area is within the Qwaira fault zone, mostly a segment called the Wadi Musa Fault which runs NS, and defines a boundary between Palaeozoic Sandstone to the west and the Upper Cretaceous marine limestones and marls to the east. It also marks a break in the topography and the beginning of a steeper slope.

A group of springs issued from the Upper Cretaceous limestone formations in the upper reaches of the basin. Recharge occurs in the upper Ash-Sharah Mountain Plateau, and springs are mostly situated at the cliffs overlooking Petra (Al-Farajat and Salameh, 2010). The natural course of the permanent water flow from Braq spring (at 1300 masl) above Wadi Hremiyyeh is through the Hremiyyeh stream, although the spring has now dried up. A Nabataean estate (Dalman, 1908; Tholbecq et al., 2018), complete with a significant set of agricultural terraces that control water flow and soil movement lies there. A Nabataean aqueduct connected the spring water from Braq to the center of Petra to Qasr il Bent (Dalman, 1908; Lindner and Hübl, 1997; Bellwald, 2008).

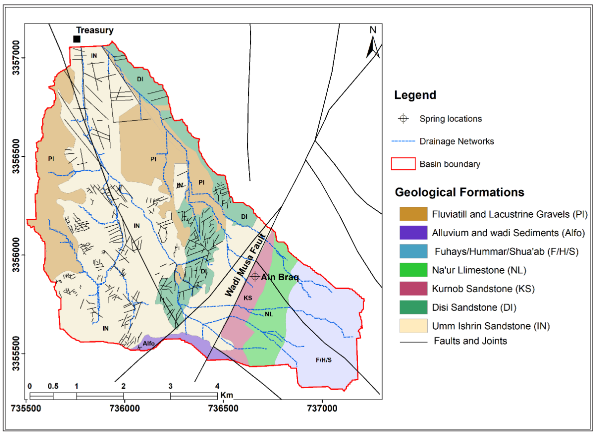

Figure 3. Geology of the study area (After Barjous, 2003).

A cliff within this segment of the tributary within the higher Upper Cretaceous limestone outcrops drops the elevation down to a ledge at 1300 masl, upon which a modern highway links Wadi Musa with At-Tayyiba. This highway has caused the diversion of most of the upstream runoff from the Braq/Hremiyyeh tributary to the adjacent Wadi Al-Madras tributary (and then to the Siq). Immediately below the ledge, the elevation continues the drop-down to the level of the Wadi Musa fault (1100 masl; Figure 4).

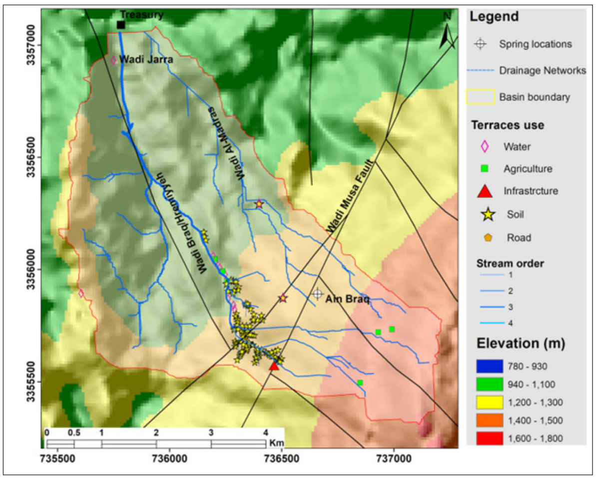

Figure 4. Topography of the study area (modified after Royal Jordanian Geographic Center).

2. Materials and Methods

A multi-disciplinary approach was used to understand the climate/tectonic/human nexus in the area. Intensive geological, hydrological, geomorphological, and archaeological surveys were conducted in the study area, coupled with soil samples gathering for texture, phytolith, and dating purposes.

2.1 Archaeology

An intensive survey of the terrace typology, method of construction, and distribution within the landscape, including spatial analysis, was conducted. Each terrace was drawn, recorded by GPS points, and described. Cultural material in association with the terraces (pot sherds) was collected, studied, and drawn.

2.2 Geomorphology

Under the geographic information system environment (GIS), a geodata base was established to organize and manage the enormous field surveys. The collected dataset contains the terraces' location using real kinematic GNSS (RTK), terrace types and usages as well as geological and hydrological information. This digital geodata base and all the necessary mapping were used to understand the geographical distribution relationship between the terrain elevation, geology, drainage, and terraces.

The watershed morphometric analysis of this study was based on the derived DEM with a spatial resolution of 2m as extracted from airborne Light detection and ranging (LiDAR), Royal Jordanian Geographic Centre (RJGC), for the selected study area. This was calibrated and referenced against a drone survey of the lower part of the drainage of Wadi Hremiyyeh. This allowed for the determination of the locations of the terraces, and the location and extent of gullying, undercutting, and carbonate deposits allowing for the inferring of how the landscape changed through time.

2.3 Soil

A recently vandalized terrace (terrace 90) at the site exposed a well-preserved burnt organic-rich horizon which allowed for the identification of botanical remains. Laboratory examination of samples obtained from the horizon provided data on seeds, pollens, and phytoliths. Phytolith separation was done using heavy liquids, whereas the seeds were separated using floatation. The pollens were extracted through chemical digestion. All of the extraction and identification of botanical remains were done at the Phytolith Research Institute in Pune, India.

In addition, samples were taken for ^{14}Cdating of charcoal from the same horizon. This was analyzed at the AMS of the A.E. LaLonde Laboratory at the University of Ottawa in Canada. Sample preparation for CO_2 purification and graphitization was conducted using the equipment and protocols outlined by (St-Jean et al., 2017). Analysis was conducted using a High Voltage Engineering (HVE) 3MV Tandem Accelerator Mass Spectrometer.

2.4 OSL ages

Conventional luminescence dating technique was applied to sediment deposits near terraces' walls in Wadi Hremiyyeh. Two sediment samples were collected from a trench dug in the slope of the wadi Hremiyyeh site (WHr1 and WHr2) at depths 50 and 80 cm. another sample was taken from a trench dug 40 cm below the former (WHr3) (Figure 5). The three samples fill at depths 50, 80, and 100 cm respectively form the surface of the first trench. The samples are assumed to represent the sediment deposited gradually by water wash along the slope of the Wadi. Water wash is expected to give full bleaching of the OSL signal before deposition. Any post-deposition disturbance will be observed by the scattering of the ages or existing age inversions. Samples were taken using metal tubes inserted horizontally in the trenches' sections. For each sample, another 200 g of sediments were taken for the environmental dose rate measurements.

Figure 5. Pits excavated for OSL dating at terrace 6.

The samples were chemically treated using 10% HCl and 30% H_2O_2 to remove calcites and organics respectively. 40% HF was used to remove any feldspars and remove the alpha outer shell for sand-sized quartz grains. Luminescence measurements and equivalent doses estimation were carried out using Risø TL/OSL reader (Model TL-DA20) equipped with blue LEDs emitting at 470 nm (~80mW.cm^{-2}) and calibrated ^{90}Sr/^{90}Y beta source delivering 0.076 Gy.s^{-1}. The luminescence signals were detected through a 7.5 mm Hoya U-340 glass filter (pass band centered on 370 nm) (Meyer et al., 2020).

Quartz luminescence signals were dominated by fast components, as shown in Figure 6 (Thomsen et al., 2008; Jain et al., 2003). Quartz equivalent doses (D_e) were estimated using the single-aliquot regenerative dose (SAR) protocol (Hansen et al., 2015). The suitability of the SAR protocol was tested using both dose recovery tests and internal performance checks. The dose recovery test was performed by bleaching twice the luminescence signals for 18 aliquots at room temperature and using blue light and intervening 10ks pause. A given dose of 15.2 Gy was given to the aliquots. SAR protocol was then applied to all aliquots using preheat/ cut the heat of 220/180 ^{o}C. The dose recovery ratio between the measured dose and the given dose was 1.021±0.007 (n=18). This proves the suitability of SAR protocol to accurately measure a known dose before any thermal treatment, therefore, all D_e estimates were measured using SAR with preheat/ cut the heat of 220/180 ^{o}C. The thermal transfer was almost negligible for the three samples (0.007±0.003 (n=9; 3 aliquots each sample). During D_e estimates, the average recycling ratio was within 10% of unity (1.018±0.011, (n=36)). The average recuperation value was ((3.5±1)%, n=36) (Murray and Wintle, 2003; Wintle and Murray, 2006).

Dose rates were measured by determining radionuclide concentrations (^{238}U, ^{232}Th, ^{226}Ra, and ^{40}K) using high-resolution gamma spectrometry. The radionuclides concentrations were then converted to infinite matrix dose rates using the updated conversion factors of Guérin et al. (2011). An internal alpha dose rate contribution of 0.020±0.002 Gy/ka in quartz (Vandenberghe et al., 2008). The cosmic dose rate was calculated following (Prescott and Hutton, 1994) an uncertainty of 5%.

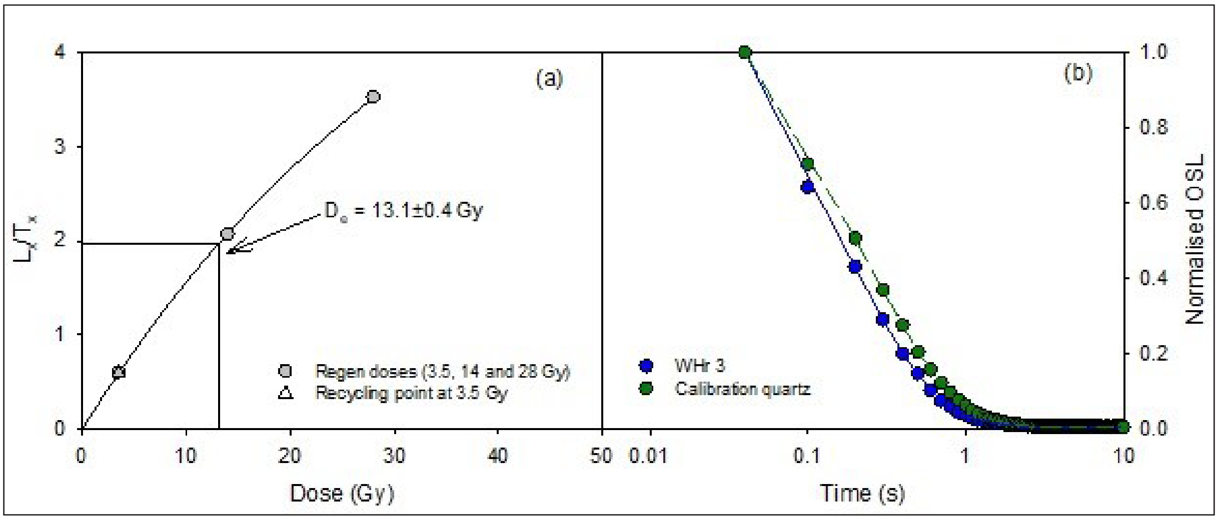

Figure 6. (a) Representative dose-response curves showing the regen doses and interpolated De for sample WHr3. (b) a typical stimulation curve for the same sample (blue continuous line) compared to a normalized stimulation curve from calibration quartz (green dashed line) using preheat/ cut the heat of 220/180 °C.

2.5 Ground Penetrating Radar

Behind terrace 88 (the upper part of the study area) a large flat area was excavated surrounded by a set of terraces to the east, south, and north (Figure 7). This area was dissected at the southeastern side by a gully and a cliff on its southwestern side. Sediment accumulation and stratigraphy were examined using a Ground Penetrating Radar (GPR) to attempt to elucidate the soil slope before the building of the terraces and to reconstruct the relationship between terrace construction and existing soil strata.

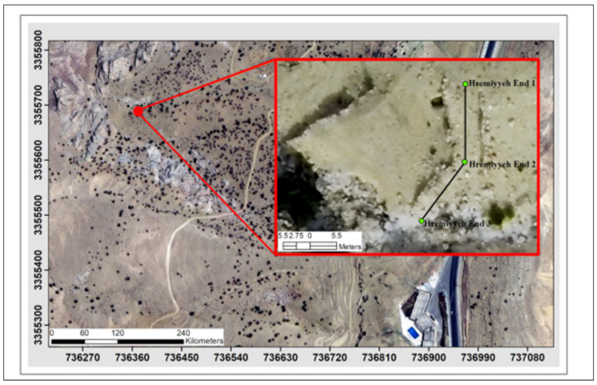

Figure 7. Lines of the GPR survey.

3. Results

A sypsometric curve allows for the understanding of the erosion state of the watershed and is used to infer the stage of development of the drainage network. Here the hypsometric curve approaches the so-called maturity stage, at least according to this degree erosion classification associated with the age of the basin (Figure 8). The Wadi Hremiyyeh hypsometric integral value is 0.37. Hypsometric integrals vary from 0 to 1, with values close to 0 being in highly eroded regions and values close to 1 in slightly eroded regions (Sarp et al., 2011; Pedrera et al., 2009).

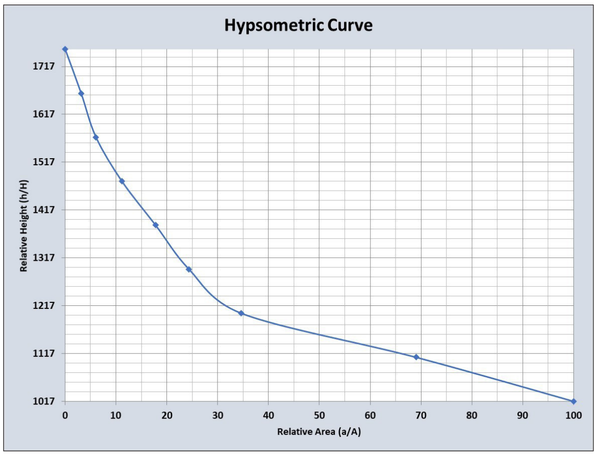

Figure 8. A hypsometric graph for Wadi Hremiyyeh. The slope break at the relative area of 37 indicates shows intermediate levels of geomorphic evolution.

The scatter pottery helped give an overall assessment of human exploitation of the studied landscape. This analysis allows relative dating as well as understanding the nature of landscape use during different periods. Figure 9 shows some of the pottery types found in the area.

The pottery sherds showed an even distribution of the surface, with a very high concentration of pottery in the middle catchment area (around terraces 29, 30). A small number of sherds were of the Iron Age II mainly around terraces 72, 73,74,76, and 84, while the dominant sherds were of E Nabataean period, with an equal amount of L Nabataean to E. Roman periods, with a very small amount of E Byzantine. Fragments of Mamluk common ware pottery were concentrated in the upper catchment area mainly in the western area around terraces (29, 30, 49, 104, 105), with a clear absence of pottery from any other Islamic periods.

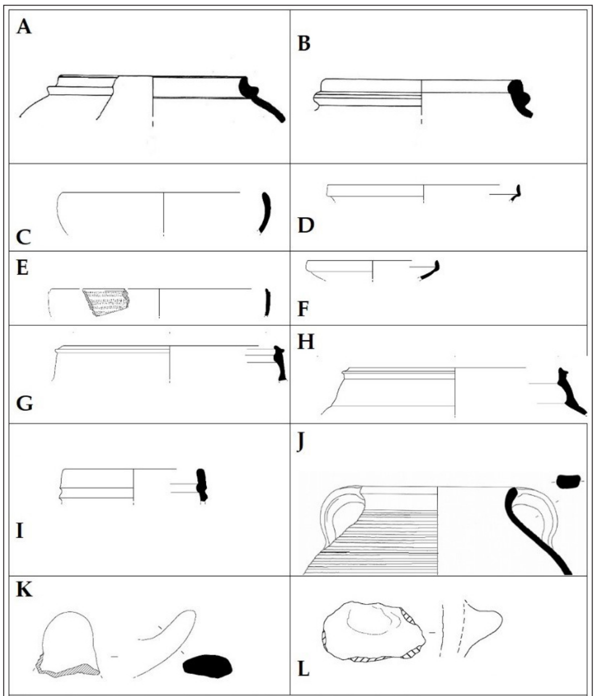

Figure showing typology of the pottery found within the study area:
A, B storage jars Iron Age II, C. Nabataean bowl, D, F Nabataean plate, E Nabataean decorated bowl, G L. Roman cooking pot, H. L. Roman jar/ cooking pot, I. Byzantine jug, J. E. Byzantine cooking pot, K, L Mamluk cooking pot.

Figure 9. Pottery types found at Wadi Hremiyyeh.

The area under consideration consists of two tributary branches that merge near terrace 30. The northern branch is smaller, yet contains several terraces (46, 52, and 95). The southern branch contains larger and more numerous terraces (49-88). In addition, the soil cover between the two branches contains a few terraces as does the southern slope that drains into the southern branch. Undercutting is seen under all of the terraces (check dams) that cross the two branches but is less clear on the slopes and in the area between them. Beyond the confluence of the branches at terrace30 (at the Wadi Musa Fault), there is evidence of both downcutting as well as carbonate deposits related to the terraces. However, the extent of the downcutting is less pronounced, as the entire slope becomes more gentle. Figure 10 shows three examples of profiles across the wadi in front of the terraces. Terrace 5 is in the lower part of the catchment, and shows slightly less than 1 m of downcutting below the terrace. Similarly, terrace 13 shows little downcutting in front of the terrace. By contrast, terrace 89 shows almost 3 m of downcutting, clearly showing a more dynamic segment of the drainage basin.

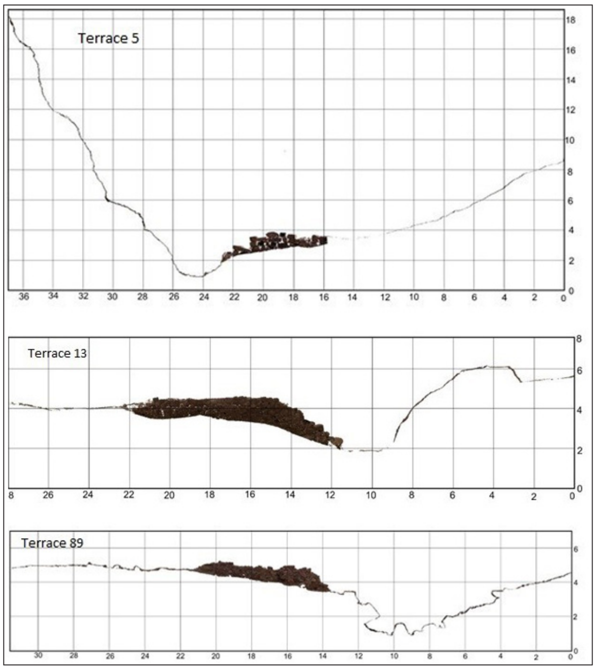

Figure 10. Profiles extracted from the 3-D scanning of the terrace system, showing the extent of downcutting below the terraces in the lower (terrace 5), middle (terrace 13), and upper (terrace 89) parts of the drainage area, All dose rate information, D_e, and calculated ages are summarized in Table 1.

Table 1. Details of the OSL measurements from the three samples behind terrace 6.

Sample	Water content	Depth (cm)	^{238}U (Bq/kg)	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)	γ dose rate (Gy/ka)	β dose rate (Gy/ka)	Dose rate (Gy/ka)	D_e (Gy)	Age (Ka)
WHr1	1.6	50	25±9	14.8±0.8	15.9±0.8	200±9	0.45±0.02	0.76±0.03	1.36±0.06	200±9	2.5±0.2
WHr2	2.3	80	17±6	17.2±0.5	14.9±0.5	141±7	0.41±0.02	0.63±0.02	1.18±0.05	141±7	2.8±0.3
WHr3	3.9	100	24±7	26.3±0.6	24.4±0.6	239±9	0.66±0.02	1.03±0.02	1.75±0.08	239±9	2.8±0.4

The luminesce ages from the two trenches at terrace 6 (Table 1) have parallel depositional records, and the samples are all consistent with each other (2.7±0.09, n=3). The highest sample is 2.5 ka, compared to the lower samples which were approximately 400 years older. Thus, deposition was active before the initiation of terrace construction.

The charred layer that was analyzed from terrace 90 (a terrace between the two branches) dated to 900-1100 CE, according to the ^{14}C analysis.

The GPR data profiles that were conducted were oriented E-W and NE-SW. The W-E profile shows the variation in the sediment accumulation thickness. It is noted that the sediment layers are compacted below a depth of 0.90m. However, from depths between 0.30-0.80m, three thick sediment layers probably reflect from three consecutive heavy floods. The NE-SW profile shows a more intense water flow/ depositional events of a relatively recent event (Figure 11). The radar cross-section suggests that the sediments behind terrace 68 are bedded towards the northeast, in the same direction of flow that existed before the construction of the terrace.

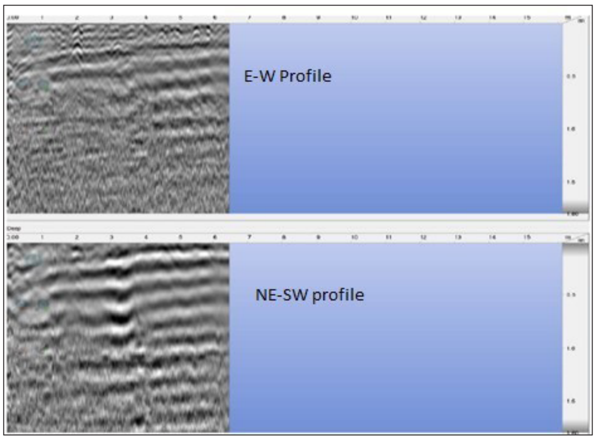

Figure 11. GPR profiles. The upper E-W profile loses evidence of stratigraphy below 90cm and shows at least 3 depositional events above. The lower NE-SW profile shows that recent depositional events as thicker and deeper, perhaps all post-dating terrace construction.

The botanic data from the charred layer contains a mix of chloridoid, festucoid, long-pointed trichome, and short-shaft dumbbell phytoliths. The dominating species were pointed trichomephytoliths followed by variants of short shaft dumbbell which is typical of grassland (Figure 12).

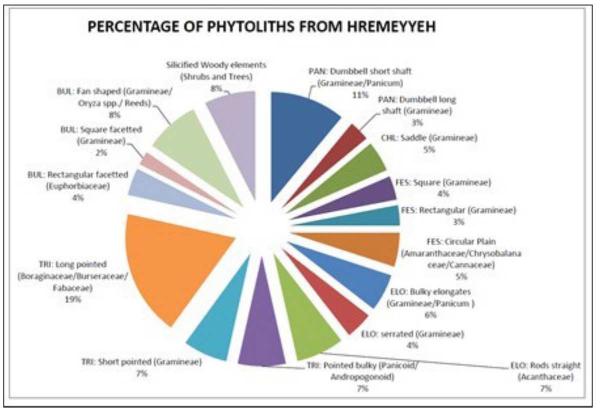

Figure 12. The various types of phytoliths found at terrace 90 at Hremiyyeh.

Half of the sample was comprised of a variety of (setaria and scirpus) wetland grasses, followed by a smaller percentage of wild species of Asphodelus and minor evidence of woods and shrubs, for example, Ziziphun seeds (Figure 13).

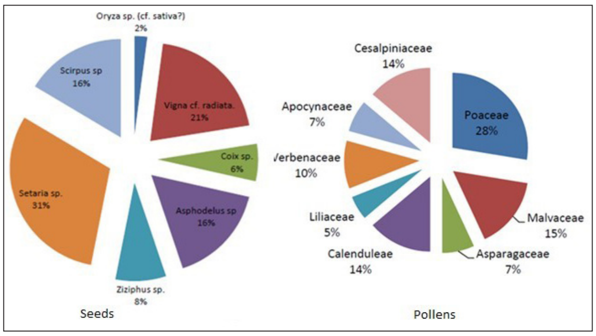

Figure 13. The seed and pollen types found at Hremiyyeh (terrace 90).

In addition to the wild grasses, evidence of cultivated plants was present by Coix, Orza Sativa, Vigna cf. Radiata (mug bean), all of which require abundant water to be grown or at least the presence of standing water. In addition to them, Asphodelus, and setaria (staple crops) were also identified. All these plants reflect a wet and warm region, which is an indication of standing water bodies that could be achieved by dams and terraces.

A small percentage of plant pollen was identified within the charred soil. Their typology confirmed the findings from both the phytoliths and seeds showing a variety of tree arboreal pollen, shrubs, and grasses. Their state of preservation was poor, probably to the alkaline nature of the soil and the high aridity which prevents their preservation. Again, the most abundant finds were for grass species of Poaceae and Malvaceae types. The arboreal species were represented by Apocynaceae and Cesalpiniaceae types (Figure 13). In addition, flowering plants were represented by the typology of Asparagaceae, Calenduleae, Liliaceae, and Verbenaceae. As pollen preservation is short, particularly in arid areas, these could represent the last phases of vegetation during the abandonment of the area and the restoration of the wild vegetation of the area.

4. Discussion

The concentration of Late Iron Age pottery in the higher areas of the drainage basin is consistent with the model put forward by Abu-Jaber et al. (2020a), whereby they viewed the absence of early evidence of human habitation in the basin as evidence of late denudation of sediments remaining from Lake Elji. Viewed in this context, it seems that the bulk of denudation at Wadi Hremiyyeh began in the Iron Age. The OSL dates of the sediments behind terrace 6 are consistent with this hypothesis. Thereafter, the terrace system was devised to manage the dynamic nature of the landscape. Initially, the interventions by terrace construction were conducted at the upper catchment area, based upon the dominant Edomite/ Iron II pottery found in the area, probably for surface water control. However, this was not enough during the Nabataean period, where the whole catchment was now the focus of larger-scale human expansion and exploitation.

Intensive terrace construction was implemented both at the upper catchment area and the lower part of the drainage basin at Hremiyyeh (Figure 2), the Wadi Musa fault defines a change in slope and the boundary between the Cretaceous and the Palaeozoic stratigraphic units in the area. Particularly, the small cracks and lateral fault zones through which water flow was extensively terraced to prevent water surface flow and to accumulate sediments. The runoff would increase on the smooth Disi sandstone dominating this area (al Qudah et al., 2016), the danger of which would affect the Khazneh Plaza, which was probably constructed as early as the second half of the first century BC (Farajat and Nawafleh, 2005). Thus the interventions at the upper catchment would fall around the second half of the 1st century BC to the first half of the 1st century AD, which is corroborated by the pottery found at the site.

In the area between the tributaries, there is little evidence for undercutting. Moreover, the amount of modern gullying is limited, despite damage to the terraces. On the contrary, the GPR profile shows that the pattern of sediment deposition changed after the terrace was built. Soil preservation and accumulation in this area is in evidence through the charred horizon preserved behind one of these terraces. The date of this horizon (10th to 11th century CE) indicates that the terraces continued accumulating sediment until that time. Moreover, the nature of botanical material found on the horizon (crops requiring abundant water) indicates that the terraces were used for agriculture at that point. Soil layers give interesting insights into the nature of these interventions as the soil layers were dipping towards the NNE from the upper SW hill towards the lower point of the valley. Owing to these factors, the Nabataeans intervened by constructing terraces into the existing soil and on the southern and western slopes of the hill. This helped stabilize the soil at these slopes.

Based on the phytolith and other botanical evidence there are indications of the climatic shift to more humid conditions, probably causing flash floods. During that time a gully seems to have developed at the western part of the middle catchment (between terrace 29 and terrace 49). During the L. Nabataean to E Roman period intensified terrace construction started within that branch to control the widening and migration of the gullying. These terraces seem to have gathered sediments towards the Byzantine period, as evidence of human settlement and agrarian activity intensification seem to occur.

The agricultural activity seems to intensify in the upper catchment during the 10th to 11th centuries, as evidenced by burning the wild bushes to create a larger area for agricultural activity as evidenced by the botanical data from the charred layer at terrace 90. These data also suggest a more humid phase in the area's history. It also seems to mark the time when some semblance of stability developed in the basin by the evidence of continued exploitation of the area until the Mamluk period.

Evidence for changes in the landscape morphology since the abandonment of the flood control system is seen in the down cutting below the terraces and the form of distinctive carbonate deposits marking the previous locations of terraces (Abu-Jaber et al., 2020b). At Wadi Hremiyyeh, the down cutting into the underlying bedrock is most pronounced in the upper tributaries to the east of the Wadi Musa Fault. Here, the interventions were the most extensive, with numerous massive check dams and terraces on the overlooking slopes. After abandonment, the siltation of the check dams was followed by breaches, gullying into the accumulated sediments, and ultimately cutting into the underlying sandstone bedrock.

The terraces built to the west of the fault retain sediments that predate the terraces themselves. This indicates that these were built into the sediment to prevent their mobilization. Here, carbonate deposits are evident behind places where the terraces had failed and the clastic sediments were moved (Figure 14). It is interesting to note that there are no carbonate deposits in front of the terraces, where presumably there were sediments before the terraces were built. Thus, the carbonate deposits were deposited as a result of the terrace building. The role of water in the deposition of carbonate has been noted previously (Abu-Jaber et al., 2020b), which suggests that the amount of water trapped in the sediments behind the dams increased significantly after the terraces were built. It is noteworthy that the terraces to the east show less carbonate deposition. This suggests that the terraces were not operational as long, or that they never became as waterlogged as the lower ones to the west.

Figure 14. Remains of terrace 25. Note the carbonate crust between the sediments and the bedrock upstream of the flow.

It is noteworthy that the drainage basin was accumulating sediment before the terracing (500-800 years BCE), and continued after the terraces were built. However, later neglect and deterioration of the terrace system resulted not only in sediment removal but also down cutting into the underlying bedrock. This is seen in the downcutting below the level of carbonate coating the sandstone substrate.

Evidence of dynamicity has been witnessed in other terraced areas of Petra. At Wadi Ghurab the soil underneath the terrace riser dates between (750-90 BCE), however, the fill in front of the terrace riser dates ranged from (110-740 CE) at 1.5m depth and (550-910CE) at 0.65m depth (Beckers et al., 2013), clearly indicating the erosion and redeposition of sediments in front of the terraces. At Wadi Sweig, the OSL dates of the sediment below the terrace riser yielded a date range between 950 and 1590 CE, while the terrace fill was older, ranging between 700 and 980 CE. An explanation for the fill being older than the riser through gully activity that caused the incision of younger sediments below the terrace riser and rebuilding activity of the riser has been put forward (Beckers et al., 2013). It is clear, however, that the terracing was done in an active wadi, and the riser was constructed to confine accumulated older terraces in the area or reconstruct an older collapsed terrace.

5. Conclusions

Iron age settlers seem to have had little influence on the topography, concentrating their efforts on the upper areas, as little of the lower catchment had been exposed, and was still buried. The Nabataeans, in what seems to have been a concerted effort to stabilize the dynamic drainage basin at Wadi Hremiyyeh, constructed a system of terraces to protect the Treasury Plaza from floods and sediments. This system came in the form of check dams to the west of the Wadi Musa Fault, terraces, gabions, and check dams in the two tributaries in the more rugged area to the east of the fault.

Gullying played an important role in reshaping the landscape and shifting the sediments, based on the huge efforts to construct dams and check dams to prevent their flow. It is plausible that headwater retreat may have grown more severe with time, making the task increasingly difficult and the effort ever more frantic.

Thus, human interventions in Wadi Hremiyyeh resulted in the modification of the landscape. This temporary stabilization resulted in delayed and then enhanced down cutting, the creation of agricultural fields, and the accumulation of carbonates. Studying terraces allow the tracing of all of these events. On a broader picture, it illustrates that the area was a site of early human interventions, trying to stop denudation at the site when the Nabataeans of Petra were benefiting from freshly exposed Palaeozoic sandstones downstream, carving their magnificent city into it.

The study clearly shows that terraces are good proxies for the reconstruction of the evolution of topographic and environmental change through time even in a confined catchment area. This is seen from the fact that they were constructed in the first place, their locations, and elevations at the time of construction, and the nature of deposits found behind and beneath them.

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