THE GREAT FLOOD OF PETRA: EVIDENCE FOR A 4TH-5TH AD CENTURY CATASTROPHIC FLOOD

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Abstract

Using palaeo-flood reconstruction techniques, it is speculated that a catastrophic flood occurred in Petra sometime in the 4th to 5th century AD. Evidence indicates that a low frequency *(p= 0.001-0.0005),* high magnitude event (4-6+ m surge, 3+ m/s velocity) would have devastated the city. Geomorphic characteristics were analysed including the (i) exacerbating channel configurations along Wādī al-Maṭāḥa, (ii) relict, extant alluvia of Disi-derived sediments along Wādī Mūsā (*in situ* exposed, and in excavations), (iii) missing pavers along the Colannaded Road that delineates the huge meanders produced during the event(s), and (iv) the location, morphology, and dimension of excavated flood-event alluvia flanking the channel of Wādī Mūsā.

Using fluvial reconstruction formulae (i.e. Manning and Chézy formulae), in conjunction with the examination of these extant features in Wadis Mu<u>dh</u>lim, Maṭāḥa and Mūsā, palaeo-reconstructions of flood height and discharge, meander dimension, and velocity enabled the re-creation of the catastrophe. Dated strata excavated above and below the event deposits narrow its occurrence between the great earthquake of May 363 AD and the mid-5th century AD. Excavated Disi deposits along the Colonnaded Road (Rooms XXVII-XXX), indicate that the water depth and torrent extent created floodwater meanders of amplitudes exceeding 45-50m, with a related stream power of 3-3.3m/s (enough to move 1-2m boulders).

Suggestions of 'periodic' and 'episodic' flooding in Petra are common *(p: 0.1-0.01),* however flood levels that were catastrophic in nature, depth, velocity and turbulence *(p: 0.005-0.0005)* have not been addressed until today. Rushing floodwaters would have entered the Bāb as-Sīq at levels up to 2 to 3 meters in depth creating surging high water that would have found the northern channels of Wādī al-Mu<u>dh</u>lim more suitable for flow. Water rushing down Wādī Maṭāḥa, would have accelerated from 0.5m/s to 1.1m/s to jump past the confluence at the Nymphaeum, to rejoin the waters in Wādī Mūsā, creating a fantastic 5-8m flood bore, accelerating to 3.3m/s along the Colonnaded Road. The water surged down the street leaving boulders, heaps of gravel and pebbles in its wake. The road would have been blanketed by 2 to 5m of sediments. The lower city centre along Wādī Mūsā would have been devastated, requiring months to years to remove the massive accumulations of boulders, gravel, sand, silt and clay.

Introduction

Early visitors and explorers in Petra frequently wrote accounts of indications and evidence of flooding along Petra's wadis, Mūsā, al-Maṭāḥa, and Abū 'Ullayqa. Discussions of sediments, boulders, and alluvium found outside the valley perched and out of place are prevalent and markedly similar in description. These observations apply to all of Petra but more commonly for the Wādī Mūsā and the channels of the Bāb as-Sīq, al-Madras, and in the wadis, ath-Thughra, Maṭāḥa and al-Mu<u>dh</u>lim. Montagu (1766), Burckhardt (1822, 1835), Stephens (1840) and LaBorde (in Croker 1836) describe possible floods, later elaborated by prominent scholars and visitors, including Brünnow and Domaszewski (1904-1909), Dalman (1908: 364), Libbey and Hoskins (1905), Kennedy (1925: 88) and Robinson (1930: 495).

When the noted Swiss explorer and geographer, Johann Burckhardt entered Petra in 1812, he wrote of the possibility of Petra's floods, in addition to its flood diversion weirs, and channelised irrigation systems. However, it is his discussion of the main channels and confluence of Wādī Mūsā and al-Wādī al-Maṭāḥa that may prove the most telling. As he exited the Sīq and walked past the theater, he rounded the bend to enter the Colonnaded Road to see, for the first time, the main valley of Petra. Astonished, he wrote

"… Here the ground is covered with heaps of hewn stones, foundations of buildings, fragments of columns, and vestiges of paved streets; all clearly indicating that a large city once existed here; on the left side of the river is a rising ground extending westwards for nearly a quarter of an hour, entirely covered with similar remains. On the right bank, where the ground is more elevated, ruins of the same description are also seen. In the valley near the river, the buildings have probably been swept away by the impetuosity of the [great] winter torrents." (Burckhardt 1822: 514).

These early travellers used terms such as flood, torrents, and deluge throughout their early reports to describe what appeared to be evidence for regular, episodic, and/or catastrophic flooding across the valley and surrounding area. Burckhardt (1835) explained that only very high water or 'winter torrents', could produce such scouring and ruination as witnessed along Wādī Mūsā and in the Valley.

These past and modern accounts (Fiema 1997; Joukowsky 1998: 390) of possible flooding in Petra explained the role of periodic or high flood stages along the primary wadis; flooding with recurrences at seasonal and episodic frequencies *(p: 0.05-0.001)*. The most commonly described high-water events indicate recurrence intervals measured in decades *(<0.005)* and not centuries or millennia *(>0.005),* unless use of words like 'deluge' were in fact, references to biblical flood magnitudes like those depicted in Genesis (7:17) (Stephens 1840). However, field observations and measurements actually indicate a higher water regime than seasonal or episodic floods – not high water that fills the channels to bankfull, but floodwater levels so high that the water would rush and surpass the channels to inundate the surrounding areas by two, four or even six meters (i.e. the Colonnaded Road, the South Portico, the Temenos Gate and the Qaṣr al-Bint).

The aim of this paper is to encourage discussion on the possibility of a catastrophic flood that may have razed and inundated the Colonnaded Road during the periods between Roman stabilisation and growth, and Byzantine expansion and reconstruction (Fiema 1998; Parr 1983). This discussion of the physical evidence and field observations will not address the impact of periodic flood events in Petra, but will explore the likelihood of a *catastrophic* flood; that is, a flood having an estimated recurrence of once every 1000-2000 years *(probability: 0.001-0.0005+)* and with flood stages that exceeded the Colonnaded Road pavement by 2-4m. Geomorphic field reconstruction indicates that Petra would have experienced a flood bore up to 10 m roaring down Wādī al-Mudhlim, rushing into Wādī al-Maṭāḥa, blasting into the confluence with Wādī Mūsā, to overrun the Nymphaeum and meander cataclysmically down the road from the Nymphaeum to the Roman Street shops and Temenos Gate, to rush past the Qaṣr al-Bint and drain down Wādī aṣ-Ṣiyyagh. The rampaging water would have left massive boulders up to 1-2m in diameter, strewn along its path with pockets along its upper limits (i.e. street shops, south portico and wadi banks).

Thus, the intent of this paper is to compile evidence for catastrophic flooding in Petra and to examine these observations using fluvial calculations and measurements, combined with conventional observations in arid-land, fluvial geomorphological research today (Graf 2002: 346).

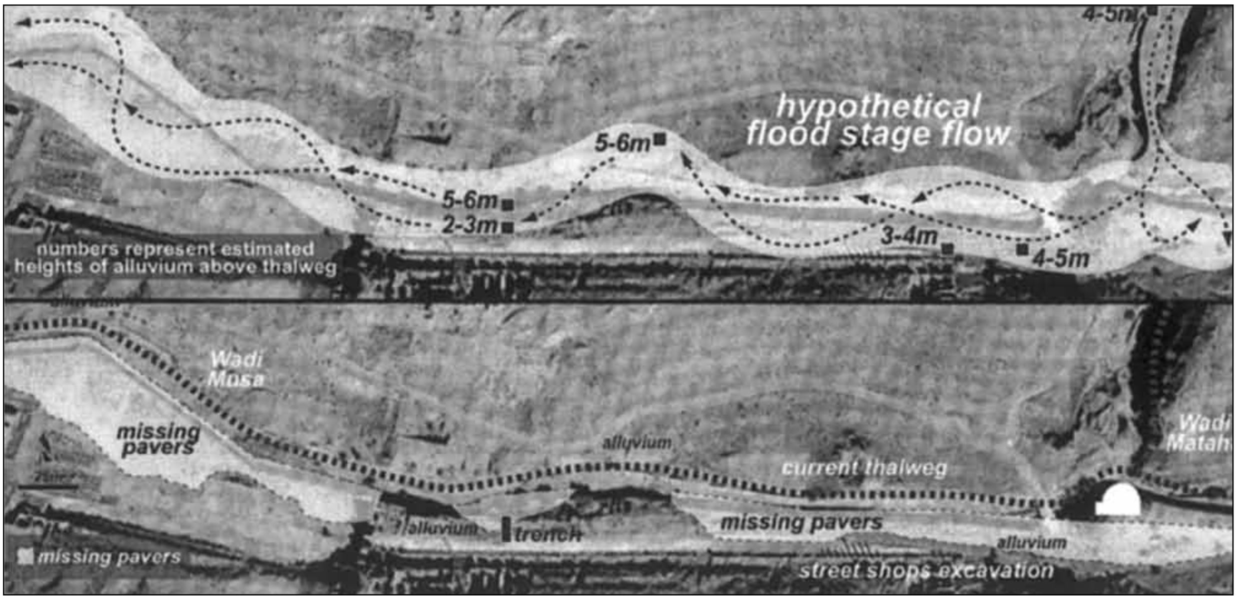
Evidence and Observations

Without written records or documentation of a catastrophic flood(s) in Petra, a compilation of circumstantial evidence is needed in order to piece together the occurrence of a flood disaster hitting the city and/or the region. The work of geomorphologists (physical geographers) has been likened to 'gumshoes in natural settings' where empirical clues of past and present environments are observed, measured, compiled and integrated in the hope of better understanding natural processes and their rates, in the past and now (Mackinder 1887). One of the underlying principles of the natural and social sciences is that natural process *rates* may change (i.e. climatic, fluvial, pluvial) but their mechanisms and influence rarely do. This concept is known as 'uniformitarianism' and is a fundamental principle of scientific method (Leopold *et al.* 1995: 544).

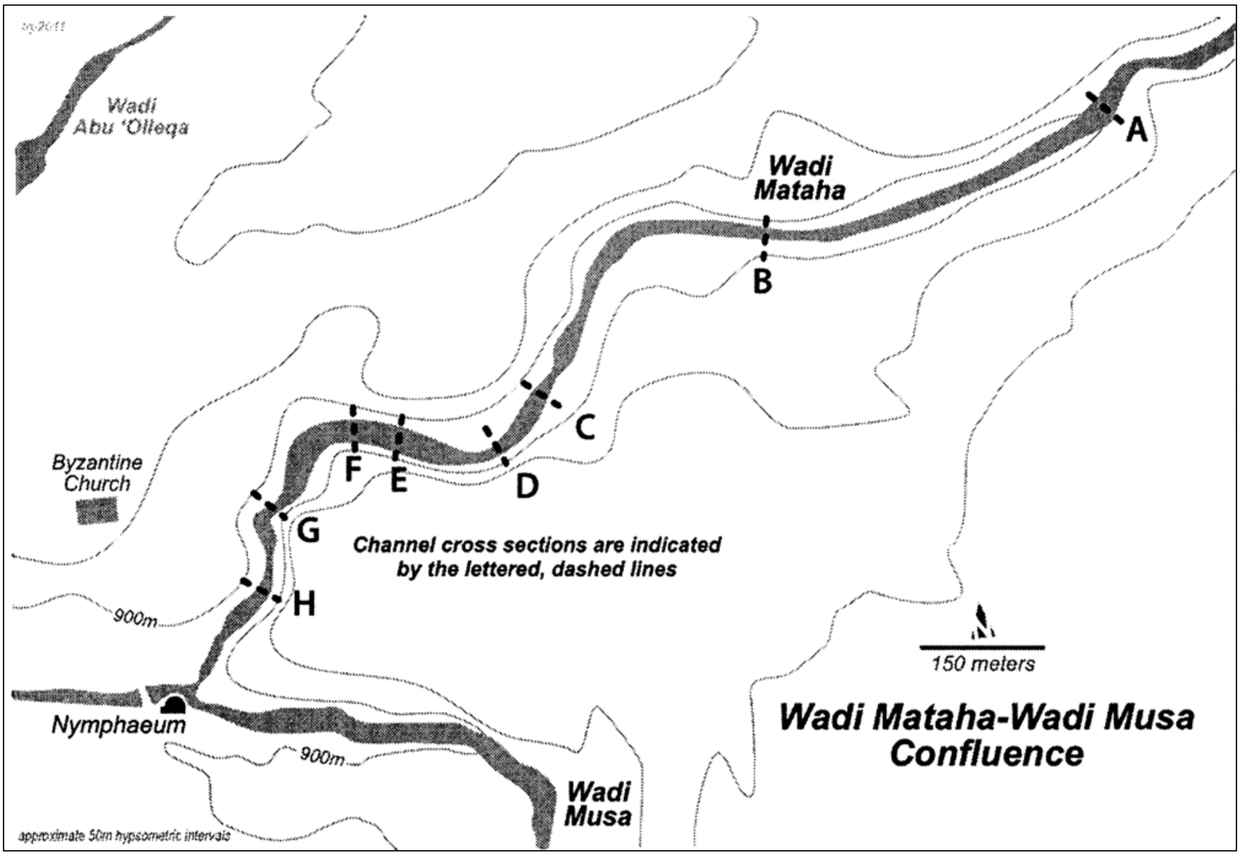
Over the past twenty years investigation of natural and anthropogenic influences responsible for the architectural deterioration in Petra (Paradise 1995, 2005, 2010) has indicated that the city centre was devastated, or at least inundated, by a flood that entered the city through al-Madras, the hewn tunnel at Bāb as-Sīq, Sīq al-Mu<u>dh</u>lim, and Wādī al-Maṭāḥa. It appears to have entered Wādī Mūsā at its confluence at the Nymphaeum to flood the Colonnaded Road, zig-zagging along Wādī Mūsā to drain down the gorges of Wādī aṣ-Ṣiyyagh into Wādī 'Araba (**Figs. 1, 2**). The geomorphic clues to these observations include (i) channel configurations that exacerbate high-water conditions such flash floods and catastrophic events, (ii) pockets of remnant sediments found suspended high above the current wadi channels, or in excavations of alluvium contemporary to the flood, and (iii) the observation and distribution of missing pavers along the Colonnaded Road.

Channel Configurations

In order to better understand the rheology, that is, the open channel flow and hydraulic power of the water in the wadis around Petra, a number of channel profiles were measured and analysed. Fourteen channel cross-sections were made from the confluence of Wādī al-Mu<u>dh</u>lim with Wādī al-Maṭāḥa, downstream along the reach of Wādī al-Maṭāḥa to its confluence with Wādī Mūsā (at the Nymphaeum). Eight of these channel cross-sections have been included in this paper due to their similar morphologies. Using *Trimble Juno* GPS devices, *Abney* and laser levels, measuring tapes, laser measuring devices, and *Nikon* digital photography, the channel shapes and dimensions were diagrammed to hectometer accuracy (5 cm) (**Figs. 2, 3**). In addition, the channel measurements were used in Manning's calculations to assess variations in channel flow regimes at varied flood heights. Water depths were ascertained using the heights of perched alluvial remnants along the wadi reach and calculations were made to determine high-flow stage and velocities. Ideally, the ages of this sediment deposition should have been determined to be contemporaneous, however it would have been cost and time-prohibitive to locate organic components for radiocarbon



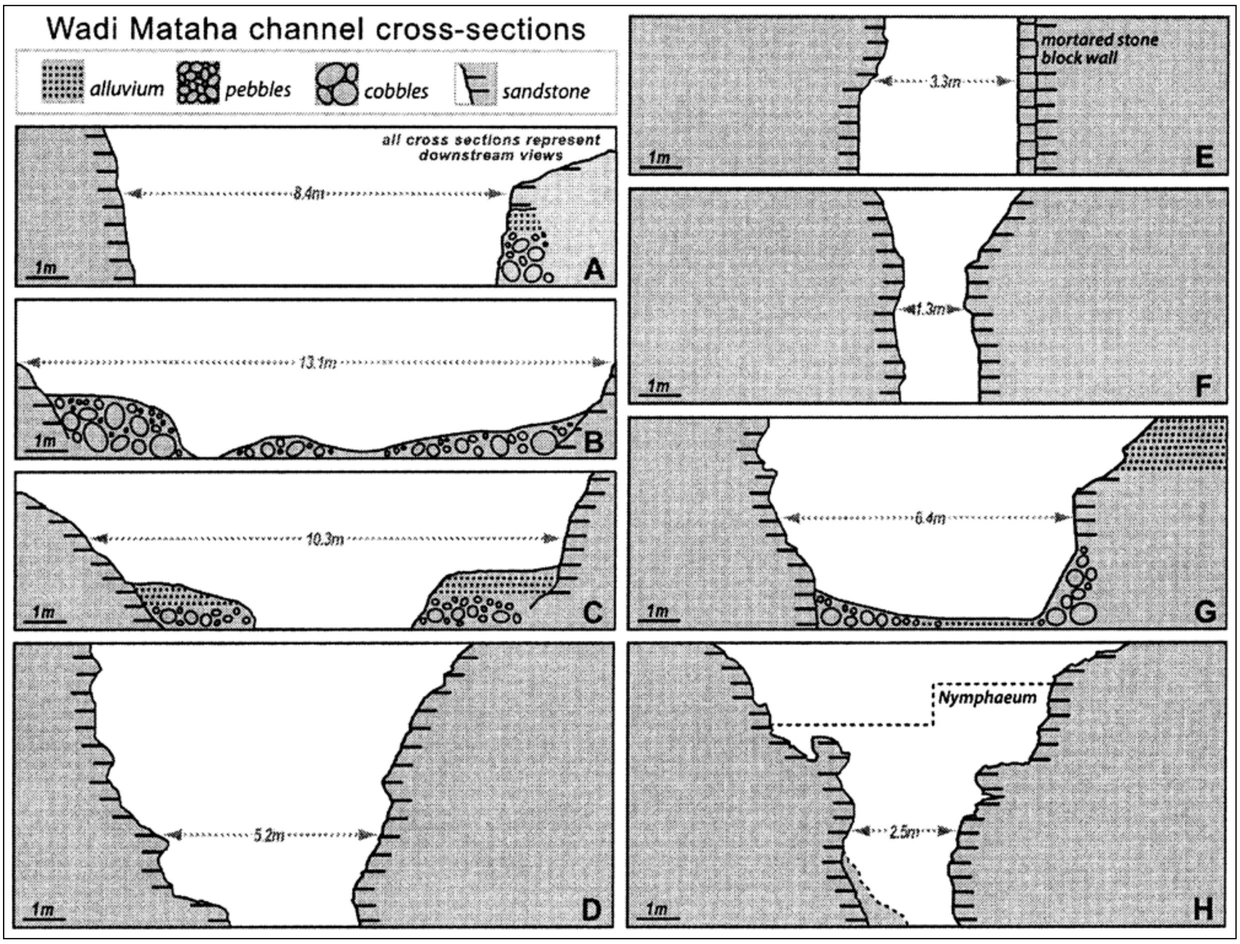
1. *Aerial imagery of Wādī Mūsā from its confluence with Wādī al-Maṭāḥa and it drainage into Wādī aṣ-Ṣiyyagh. The diptych represents the duplicate images with the upper image illustrating the hypothetical catastrophic flood stage regime (6-8m stage), and relict alluvium heights noted above the channel thalweg. The lower image illustrates the area of (i) missing pavers, (ii) alluvium trench (Parr 1983), (iii) the location of the excavated street shops (Fiema 1998), and (iv) the current channel thalweg.*



2. This map represents the extent and configuration of the wadi channels and confluence of Wādī al-Maṭāḥa and Wādī Mūsā. The confluence is marked by the location of the Nymphaeum (ca. 1st Century AD), where the wadi drains to the west (left). Wādī Maṭāḥa originates with the primary discharge diverted from the barrier dam and culvert at the Bāb as-Sīq into Wādī al-Mu<u>dh</u>lim, passing into and through the hewn tunnel into Sīq al-Mu<u>dh</u>lim and converging with Wādī Maṭāḥa to the east of Jabal al-Khubtha.

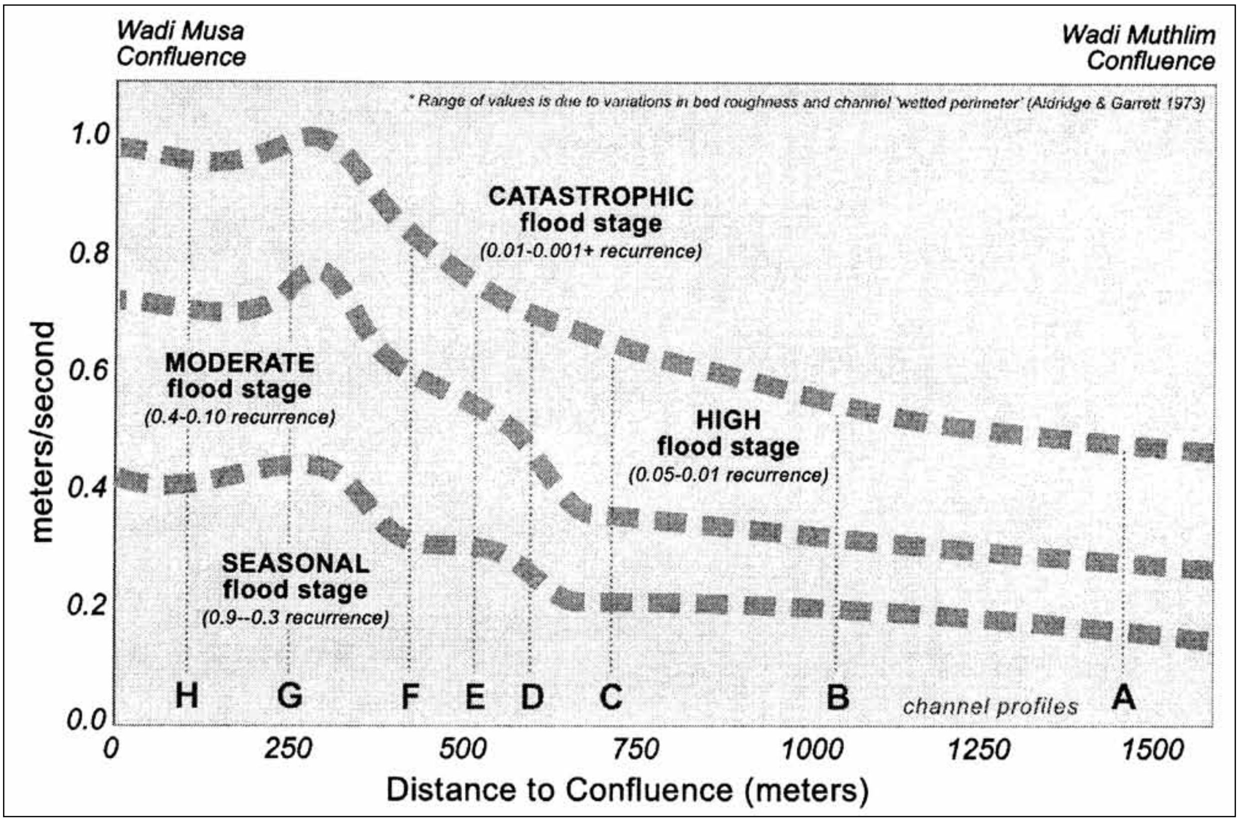
dating or optically stimulated luminescence (OSL) (Prescott and Robertson 1997). Hence, the greatest height above the channel *thalweg* (deepest portion of channel) was determined from the remnant alluvia and/or fluvially eroded features prevalent throughout Sīq al-Mu<u>dh</u>lim and the narrow channel near the Maṭāḥa-Mūsā confluence. These heights (in metres) were used in flood stage and velocity determinations (**Figs. 3, 4**). The magnitude of the results was startling, supporting the occurrence of a catastrophic flood in this arid landscape of confined channels and sandstone banks.

The use of fluvial formulae in the analysis of palaeo-fluvial environments is conventional and proven in both prediction and reconstruction. Through the use of the Manning's Equation(s) (Leopold *et al.* 1995), calculations indicated that as water at various levels in Wādī al-Maṭāḥa moves downstream the channel narrows in width, forcing water to rise in depth and increase in velocity. To confirm this intuitive assessment, alluvium was observed and found higher and higher above the channel as the reach flows from its upper confluence with Wādī al-Mudhlim to its merging with Wādī Mūsā (**Fig. 3**). Assuming that the water source was being predominantly supplied upstream (at Bāb as-Sīq or above al-Maṭāḥa as stream input and/or rainfall), and not simply from above the channel in question (direct rainfall) we can estimate that the channel discharge (volume/time) remained relatively constant or a little-moderate increase. If this was the case, then water in the channel would have risen dramatically from channel narrowing, and would have increased in velocity – which was confirmed through the Manning's calculations (Barnes 1967). Velocity was determined to double from 0.2 to 0.4m/p/s (0.7 to 1.5kph) at the upper reaches (cross sections



3. *This multiple diagram represents the various channel wall configurations between the upper reaches of Wādī al-Maṭāḥa near the opening of Sīq al-Mudhlim (A), down the wadi and passing below Dorotheo's House, Sextius Florentinus, and the Royal Tombs. Wādī al-Maṭāḥa enters a small 'Sīq' as it approaches the confluence with Wādī Mūsā (H) directly below the Nymphaeum along the Colonnaded Road. Flood stages must have exceeded 6 to 7m to 'jump' the Nymphaeum and flow across the Colonnaded Road (then and now). An additional 1-2 meters of flood stage (for a total of 7 to 9m) would be required to reach and deposit the 0.2 to 0.8m alluvial beds found in (i) the Roman Street Shops (Fiema 1998), (ii) the excavated trench at the Temenos (Parr 1983), and (iii) the remnant sediments and abrasion observed along Wadis al-Maṭāḥa, Mūsā and al-Mudhlim.*
Note that the Wādī Maṭāḥa channel narrows as it nears its confluence with Wādī Mūsā. Also, fewer channel sediments are observed farther down the channel; the 'wetted perimeter' becomes increasingly slickrock and bare sandstone. This geomorphic constriction facilitates high flood risk by creating a 'hydraulic head' whereby water levels rise as discharge remains constant or increases (Graf 2002).

A, B, C) to 0.4 to 1.0m/p/s (1.4 to 3.6kph) along the lower reaches nearing Wādī Mūsā (cross section F, G, H). This increase in velocity would occur in conjunction with an increase in water depth (height), raising water levels three to four times. With a channel width nearly four times larger at A (at the Mudhlim), versus H (near the Nymphaeum), it is both verifiable and intuitive that a high to severe flood stage would breach the wadi wall at the Nymphaeum; a catastrophic flood event would not only surpass the channel bank, but would overrun the Colonnaded Road's flanking structures: the Roman Street shops, Great Temple, Pool Complex, *Propylaeum*, South Portico, Temenos Gate and onto the Qaṣr al-Bint. The flat area that we now see and walk along the lower portion of Wādī Mūsā (near the restaurants, museum and restrooms) would have been inundated with at least 2m, up to 5m of rushing water (based on Chézy, Manning models: Limerinos 1970). These fast-moving and deep currents would have created turbulence so great that it would have eroded road pavers and removed all road substrates – as currently evi-

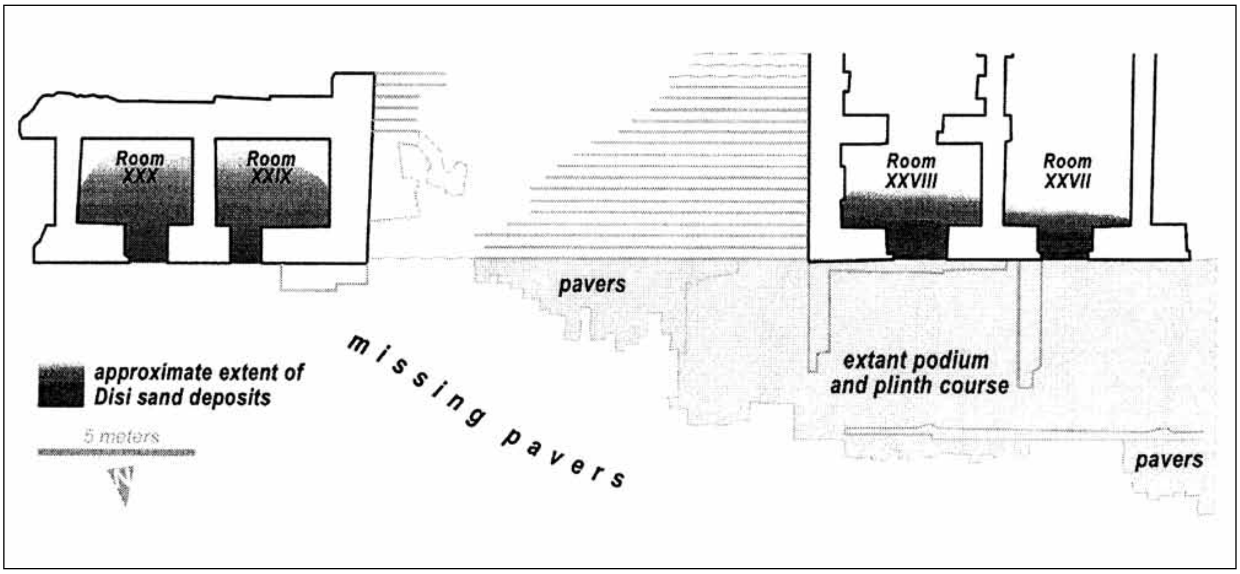


4. Manning's Equation (Leopold et al. 1995) is a conventional tool used in the calculation of stream velocity and flood levels; these were used in estimating flood stages in Petra's past. Using channel configurations, slope, and bed roughness it was estimated that water draining from Bāb as-Siq through the Tunnel, into Wadi and Sīq al-Mudhlim, and into Wādī Maṭāḥa accelerated as it reached the confluence of Wādī Mūsā and Wādī al-Maṭāḥa due to the narrowing of channel, channel wall changes from loose sand and gravel to slickrock, and a relative straightening of the channel reach. These graphs indicate that during various flood stages, the water not only increased in velocity two to three times (from 0.4 to 0.9 meters per second), but also doubled in height above the thalweg (3-5 meters) in moderate to high flood stages, but also trebled (6-9 meters) in those rare catastrophic flood events – having a flood recurrence interval of 500 to 1000 years (0.005-0.001). Moreover, meander wavelength reconstruction from the Street Shops (Fiema 1998) indicates that the floodwater velocity exiting Wādī al-Maṭāḥa would have trebled again to 3.0-3.3m/s; this would create destruction and havoc along the Colonnaded Road with up to 18-25 feet of water rushing down through Petra as it entered at the confluence of Wādī Mūsā with Wādī al-Maṭāḥa.

denced by the missing pavement stones (**Figs. 1, 5, 6, 7**). It would have also redistributed significant amounts of sediments from the upstream sediment reservoirs in channels, sandbars, and adjacent dunes, into the downstream channels and floodplains creating a lateral and distal deposition of sands, silts, and clays, to the vertical and graded relocation of clay, sand, gravel, pebbles, and boulders (**Figs. 1, 6, 7**).

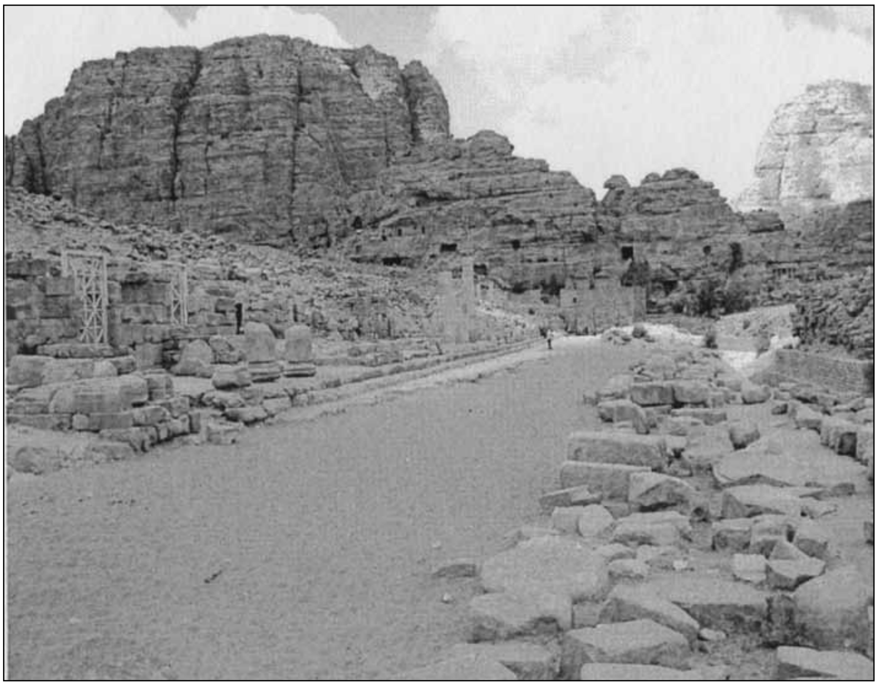
Missing Street Pavement

The most ubiquitous and yet obvious evidence of a catastrophic flood in Petra may lie beneath our feet. Aerial imagery and on-the-ground observation show huge areas of limestone pavers are missing from the surface of the Colonnaded Road from the Nymphaeum, past the South Portico, through the Temenos Gate, to the Qaṣr al-Bint. The missing paving stones are not arbitrarily missing (or stolen) but are absent in patterns that create broad arcing voids. These arcing forms undulate in configurations similar to a meandering stream channel, and in repeated, cyclic forms that further corroborate a fluvial influence. The largest swath of missing pavers occurs at the confluence of Wādī Mūsā and al-Maṭāḥa, to decrease downstream, flanking the reconstructed colonnade to its south. The pavement *lacuna* decreases towards the colonnade, to appear again near the Temenos Gate



5. This map represents the 'Roman' Street Shops excavated through the American Center of Oriental Research (ACOR) under the supervision of Dr Z. Fiema (1998). In the main room excavations of XXX – XXVII, sandy, silt and clay deposits were discovered that were all characteristic of the alluvium from the weather Disi Sandstones of Bāb as-Sīq, Jabal al-Khubtha, and Wādī al-Mudhlim. The existence of these alluvial deposits is indicative of their fluvial relocation and redistribution through the catastrophic flooding down Wadis al-Mudhim into Wādī al-Maṭāḥa, and into and across its confluences with Wādī Mūsā. Note how the arcing nature of the deposits and the missing street pavers represents the arc of a large meander. Such a large amplitude for a meander is indicative of high-flood regime discharge in these wadi channels.

6. Looking west and downstream along the Colonnaded Road and the channel and thalweg of Wādī Mūsā, the height of the alluvial sediments on both side of the channel are roughly 2 to 4 meters above the road pavement, or 4-6m above the channel thalweg. Both indicated alluvial layers would have been located on the outer bend of the flood stage meanders – the most common area for lateral and vertical flood stage deposition (Leopold et al. 1995).



7. Photograph looking west along the Colonnaded Road from the Nymphaeum to the Temenos Gate. The limestone pavers are missing between the excavated Street Shops (with green gated entries) and the wadi edge (the far right). However, the pavers are visibly in situ farther down the roadway towards the Temenos Gate (and trenched area of flood alluvium from Parr 1983). Note than the arcing form of the missing pavement follows a shape typical of a stream or wadi meander. The larger meander amplitude (width of meander arc) strongly suggests a dramatic increase in stream discharge, significantly greater than seasonal or episodic flooding.

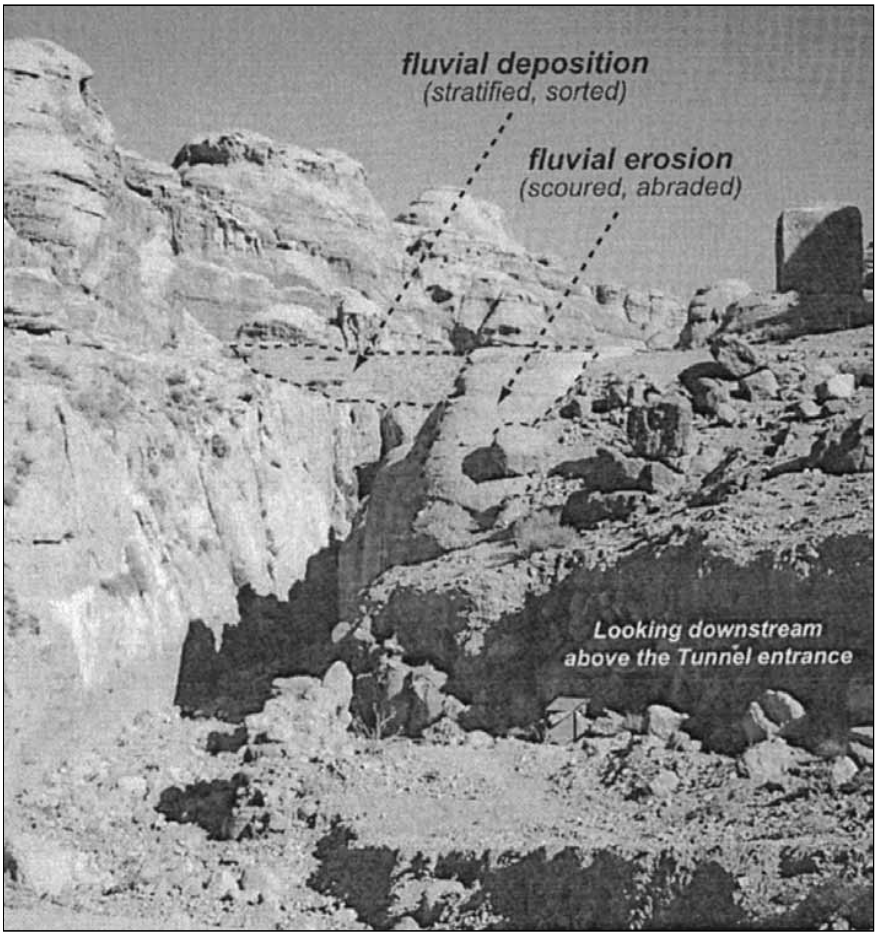
and South Portico (**Figs. 1, 5, 6, 7**). So why do the missing Colonnaded Street pavers exhibit a pattern of *lacunae*, and not an arbitrary arrangement of missing and extent pavement stones? The proximity of the pavement *lacunae* to the wadi channel, and the characteristic arcing configuration all indicate that their removal was a function of fluvially-generated turbulence – a regular result of the violent power of high floodwaters, exceeding channels that are irregularly-shaped smoothed and weathered sandstone and confined, like those of Petra's wadis.

Redistributed and Relict Alluvium

During flood events, with the fluvial relocation of upstream sediments and alluvium into the downstream environments, also comes a noticeable redistribution of different sediment materials. The Disi sandstone represents Petra's overlying rock bed, easily seen across the region as the buff-coloured sandstone that comprises most of Jabal al-Khubtha, and the Djinn blocks and rounded rockforms at Bāb as-Sīq. Their buff and beige colouring marks their sharp contrast to Petra's lower reddish rocks of the Umm Ishrin Formation: dark-red, mustard, magenta, and brown tones made famous in J. W. Burgon's award-winning poem as 'rose-red'. It is these deposits of the Disi sandstone that can be found and observed across the main valley of Petra, mobilized above Wādī al-Mudhlim, to become transported into Wādī al-Maṭāḥa and into Wādī Mūsā below. Their buff-colour can be found as residual alluvium throughout the valley. As Burckhardt (1822) and Robinson (1930: 495) observed, the water channel to the north of the Sīq (through the tunnel and into Wādī al-Mudhlim) may have been a primary channel for practical purposes, as redirected and/or facilitated by early Nabataean and/or Roman engineers. Since the Sīq was the main thoroughfare into Petra, redirecting floodwaters from entering the Sīq was crucial to the well-being of Petra's commerce and society. Floodwaters draining towards the Sīq were diverted through the tunnel ultimately merging downstream with Wādī Mūsā at the Nymphaeum (ideally). However, if and when the culvert and weir diversion should fail, rushing water would (and indeed has) rushed into and down the Sīq. This was indeed the case in 1963, when 22 visitors died from flash-flooding. The floodwater depths in the Sīq were described as at least 4 to 5m (Time Magazine, April 19, 1963) yet the *Khazneh* was spared great damage and the floodwaters drained into the outer Sīq. After the disaster engineers decided to build a dam, weir, and culvert to mitigate against any flood recurrence, however they unearthed classical period structures (Nabataean?) that were used exactly for that purpose: to divert floodwaters from Wādī Mūsā into Wādī al-Mudhlim at the Sīq's entrance.

Floodwaters exceeding 4 to 5m would have devastating effects anywhere in Petra, however in narrow, sandstone channels such as in Wādī Mūsā, Mudhlim, and Maṭāḥa, it would be disastrous and in confined spaces such as the tunnel, it would be especially high and dangerous. This would have been the case if a catastrophic flood(s) had devastated the main valley in the 4th to 5th century AD. Water would have been diverted past the Sīq to enter the tunnel, creating a 'hydraulic head' backing up to raise water levels behind the tunnel and subsequently over the tunnel. Slow-water areas would have experienced deposition (above), and fast-water areas would have experienced erosion and scouring (to the sides) (**Fig. 8**). Currently along Wādī al-Maṭāḥa, similar deposition may be found in areas of slower velocity upstream (broad flat, gravelly channels) and erosion and scouring may be observed in areas of high velocity flow downstream (narrow, high sandstone) (**Figs. 2, 3, 4**).

Farther downstream, perched pockets of Disi-derived alluvium can be observed along Wādī Mūsā in the main valley, indicating the fluvial transfer of sediments from upper Wādī Mūsā above the Sīq and Mudhlim above the Tunnel. At levels 3 to 6m above the channel thalweg, alluvia is found across from the Roman Street shops and Nymphaeum, and below the Byzantine Church and Temple of the Winged Lions (**Figs. 1, 5, 6**). Moreover and more importantly, is the discovery of Disi sandstone or mixed Disi-Umm Ishrin derived sediments in the excavations of Fiema (1998) and Parr (1960, 1983). In Fiema's excavations of the Roman Street shops (#40-38), buff-colored, undisturbed and non-occupation beds were found in Rooms XXVII-XXX. These were analysed and assessed by the author as part of the Roman Street Project in 1997 (Fiema 1998). Fiema describes them as 'uncleared sandy deposits' measuring 0.15 to 0.25m in depth (Fiema 1998), fronting Rooms



8. Looking towards the Tunnel at the confluence of Wādī Mūsā and Wādī al-Mudhlim, in the Bāb as-Sīq (Tunnel is beyond the shadows in the channel), you can see the remnant patches of fluvial deposition and erosion created by high water events. Discharge this great, and water stages this high represent a catastrophic event and not a seasonal or episodic flood stage. The height of both the scoured area and alluvium are the same at approximately 7-9m above the channel thalweg, indicating a flood stage similar in height to the event that created extensive deposition past the confluence of Wādī al-Mudhlim with Wādī Mūsā at the Nymphaeum. Also note the characteristic buff-color of the Disi Sandstone here, is markedly different from the dark reddish colors of the Umm Ishrin Sandstone in the Valley below.

XXV and XXVI and facing the wadi channel, decreasing in thickness with distance from the *thalweg*. The bed colour, uniformity, composition, graded structure, and particle distribution indicates that they were deposited through the bankfull flooding and fluvial deposition of the adjacent wadi (to the north) and derived from the Disi sandstone upstream and beyond the confluence of Wādī al-Maṭāḥa and Wādī Mūsā (**Fig. 9**). During the excavation period, analysis of these non-occupation beds was made for particle size, type and distribution, graded structure and colour. Fiema (1998) identified the various locations of the salt-silt deposits with the assessment by the author in 1997:

"Two columns are located in that gallery, standing directly against the north face of Wall BB… with the bases of these columns being under the uncleared sandy deposits. It appears the columns are in situ" (Fiema 1998: 411).

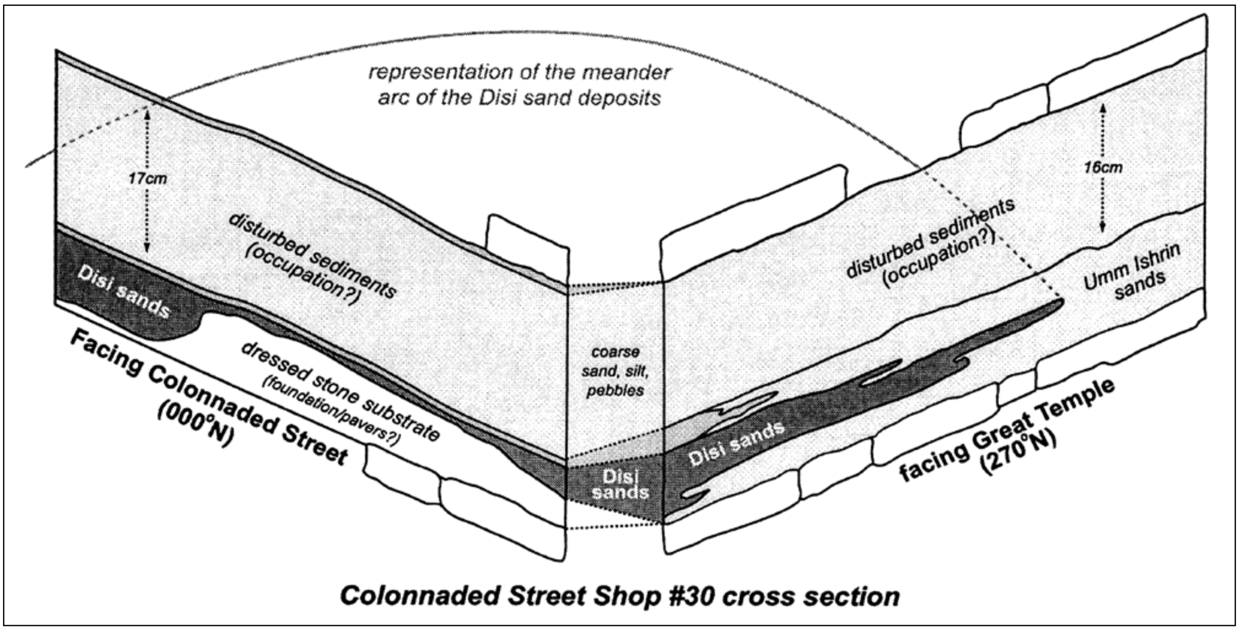
"A layered deposit of sand and coarse clayish-silt, ca. 0.15-28 m deep… characteristic of flood event morphology, contained four coins… pre-AD 363 period. This layer was covered by a very heterogenous layer of silt with an abundance of cultural material (57 coins, 13 post 363 AD issue). It is possible that the final occupation (was) before the flood… but might have happened sometime in the early to mid-fifth century AD… followed by the collapse of the arches. On the other hand, it is possible that the coins belong to two completely separate phases of occupation, isolated from each other both spatially and temporally by the flooding incident" (Fiema 1998: 413).

"… in the adjacent room, the alluvial, flood-related sand and gravel was found deposited directly over the beaten-earth floor. Out of the 44 coins, 14 were minted after AD 363" (Fiema 1998: 416).

"… the alluvial character of the lowermost deposits is common everywhere within the excavated area" (Fiema 1998: 417).

"Traces of the ancient meandering of the wadi banks were noted in Room XXVII. Post-earthquake (May 363) occupation, possibly interrupted by a flood episode, continued until the mid-fifth century AD" (Fiema 1998: 418).

Not only do Fiema's references to the Disi sandstone deposits ascertain the depth, extent



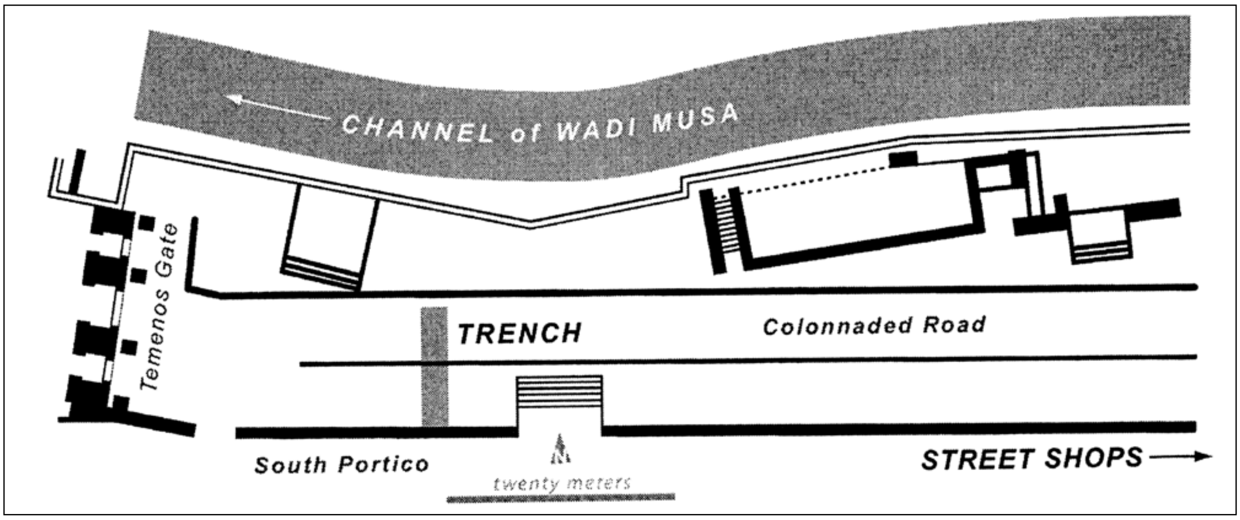
9. These two cross section profiles represent two documented excavations at the Street Shop #30 along the Colonnaded Road. The left-hand profile was excavated facing the Colonnaded Street (~000ºN), while the right-hand profile was found during a sondage excavation within the shop, extent aligned with the western wall (~270ºN). Note the light-colored sands from the Disi Formation (from the Bāb as-Sīq) were unearthed here and can be found decreasing in extent with distance from the street and wadi channel. Their occurrence and distribution indicate a lateral and vertical deposition from Wādī Mūsā, via Wādī al-Maṭāḥa, via Wādī al-Mudhlim. Local deposition would consist primarily of the Umm Ishrin sandstone particles; a distinctive darker red color, rather than the lighter buff colors of the Disi. These profiles were measured, assessed, and documented by the author during the excavation field season (Fiema 1998).

and locations of the relocated Disi sands, but when examining the soundings (sondage), Fiema and the author were also able to observe the arcing nature of the deposits (in Room XXVII) indicating their origin as the outside arc of an 'ancient meander' (Fiema 1998). However often the term episodic has been used to assess possible flood frequency in Petra by assorted visitors and researchers, it must be noted that a dryland flood that creates a 3-5 m over-bankfull discharge in a wadi like al-Maṭāḥa or Mūsā (relatively small, with alluvial and sandstone channels) would not be a seasonal or 'episodic' event at all, but one severe or catastrophic (Leopold *et al*. 1995). When looking at annual flood stages in Petra and the region, and talking with local B'doul and Wādī Mūsā residents, a flood bore of 3 to 5+ m is unique and most probably never seen in Wādī Mūsā. In these wadi channels such a flood event represents a disaster of epic proportions, that is, a 1000 to 2000+ year event.

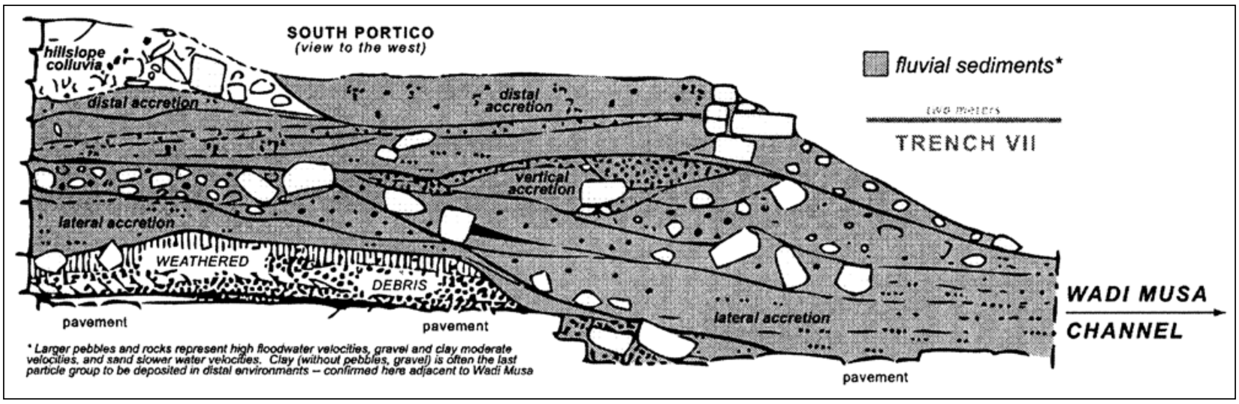
By using conventional calculations for flood morphology, stream velocity can be calculated by assessing slope, meander size, and fluvial constants. Based on modifications to Chézy and Darcy-Weisbach calculations (Bjerklie 2007), flood-level velocities that would produce such a broad meander (45-50 m wavelength) would be rushing at approximately 3.0 to 3.3 m/s, or three times greater than what would be considered a severe or catastrophic flood (Kleinhans and Van der Berg 2010) (**Figs. 4, 5**). The flood that produced the excavated meander deposits in the Roman Street shops was no episodic or high flood but rather one that was catastrophic in Petra's city and must have dramatically affected its society and economy. The turbulence produced would have lifted the pavers as well, before the decreasing floodwater depths and velocities began to deposit its bedload of boulders, gravel, sand, silt and clay from the Disi sandstone above and the neighbouring Umm Ishrin sandstone below. What is unusual in this reasoning, and creates new questions, is why the deposits found in the Roman Street shops comprised only Disi sands and not a combination of Disi and Umm Ishrin sands? Such a wall of rushing water is entraining and transporting bed materials as it rushes down the wadis. So, why are the non-occupied, sandy beds comprised of what appears to be solely the Disi sands from Wādī al-Mu<u>dh</u>lim and upstream? One reason seems clear; that the first flood bore was filled and buoyant with the Disi sands. The calculated floodwater velocities in Wādī al-Maṭāḥa at 0.7 to 1.0+ m/s (**Fig. 4**) would have been ideal for the entrainment and transportation of sands. Once the flood bore rushed from Wādī al-Maṭāḥa, upon merging with Wādī Mūsā at the Nymphaeum, the increasing velocities (~3 m/s) would have been able to mobilize massive boulders one meter or more in diameter (Leopold *et al.* 1995), in addition to the unbridled destruction that would be sustained from such sediment, pebble, and boulder-filled rushing water. Therefore it is speculated that the first floodwave was filled with entrained Disi sands, violently rushing down Wādī al-Maṭāḥa to deposit its bedload upon its abrupt stop at the walls of the Roman Street shops across from the Nymphaeum (**Figs. 5, 9**). The sharp decrease in velocity would have been sufficient to cause the rushing water to drop its sediments of the Disi sands upstream (near Rooms XXVII-XXX).

In Parr's notable excavation of the Colonnaded Road at the South Portico and Temenos Gate (1983), his cross-sections clearly show the occurrence and particle distribution of similar fluvial deposits. Not only do these sediments indicate typical lateral and vertical fluvial deposition but they also exhibit a distance decrease from the wadi, thinning in thickness with distance from the current *thalweg* (**Figs. 10, 11**). This supports the hypothesis that these were Disi sands carried by the rushing floodwaters to be deposited along the Colonnaded Road at depths up to 2 to 4m above the paved surface, and 4 to 7m above the channel *thalweg*. The distance of these beds from the wadi *thalweg* also matches those of the deposits unearthed in Rooms XXX-XXVII. This corroborates the calculations that suggest the water was indeed rushing, turbulent, and fast moving upon exiting the narrows at the confluence of Wādī al-Maṭāḥa into Wādī Mūsā. Such a fast-moving bore may have topped the bare sandstone facing the Nymphaeum to blast over and onto the roadway to rush in sweeping meanders down the wadi channel, sloshing from the South Portico to the valley wall and back until it exited down Wādī aṣ-Ṣiyyagh.

The thickest portion of the cross section alone



10. This map represents the location along the Colonnaded Road of the trench that exhibits the flood alluvium, excavated by Parr (1983). The configuration of the current bank, drainage geomorphology, and thalweg indicate that the current channel form and thalweg are the same or close to the channel form 1500 to 2100 years ago, however channel revetments and channel walls have been reconstructed and/or constructed in recent years. Note that the trench was located at the southern edge of the outside bend in the wadi meander – the area that would experience the greatest bank breach and out-of-bank deposition (both vertical and lateral accretion).



11. This map represents a cross section of the sediments excavated along the Colonnaded Road by Parr (1983). The indicated sediments are typical of fluvially-deposited sediments (alluvium) probably due to the flood event deposition along Wādī Mūsā, from drainage into the confluence via Wādī al-Maṭāḥa. This alluvium measures 3m (10') in depth atop the pavement, and 5m to 6m (16'-19') above the wadi thalweg (deepest part of channel). At a point where the current channel is 2 to 3m below the road, these sediments represent a flood stage of up to 6m or possibly up to 7m (19'-22') – a stage that matches fluvial sediments along Wādī Mūsā, its upstream confluence at the Nymphaeum, and the Wādī al-Maṭāḥa reach upstream.
Note that lenses of clays, silt and sand are interbedded with large boulders and gravel indicating a series of pulse of high velocity (2-3m/s) and low velocity water (<1m/s). Meander amplitude reconstruction from the Street Shop excavation (XXVII-XXX) indicates that the flood velocity was able to entrain and transport boulders 1-2m in diameter.

represents a minimum depth of 3-4m above the road pavement (Parr 1983), and 5 to 6m (16-20') above the adjacent channel *thalweg*. Flood-derived alluvia only represent the lower water levels, so 6m sediment depths would mean at least 6m of water depth (possible up to 8m water stage). This means that all of lower Petra would have been inundated for hours, only to recede leaving behind 4 to 6m of clay, gravel, sand and boulders strewn and cluttered across the city. What would have followed would have been a monumental task of sediment removal, and the similarly monumental task of 'kick-starting' social order and Petra's economy following the deaths, injuries and damages sustained from such a natural tragedy.

Summary

The aspects of the (i) unusual channel configurations along Wādī al-Maṭāḥa, (ii) relict alluvia of Disi-derived sediments along Wādī Mūsā (*in situ* and in excavations), and (iii) the missing pavers along the Colonnaded Road, all represent robust evidence, however circumstantial, of catastrophic flood(s) that have left clues and evidence across Petra. Using conventional fluvial reconstruction techniques (i.e. Manning, Chézy), in conjunction with the examination and assessment of various relict, and extant landscape features in Wādī al-Mudhlim, al-Maṭāḥa and Mūsā, palaeo-reconstructions of flood height and discharge, meander dimension, and velocity enabled the re-creation of a probable catastrophic flood in Petra's late Roman-early Byzantine history (Leopold *et al.* 1995). Suggestions of 'periodic' and 'episodic' flooding in Petra are prevalent *(p: 0.1-0.01),* however flood levels that were catastrophic in nature, depth, velocity and turbulence *(p: 0.005-0.0005)*, have not been addressed until today. It was the intent of this research to stimulate a new discussion on this probability of a significant and historic flood, with a new perspective on the occurrence of undisturbed, buff to yellow-coloured silt/sandy deposits observed and/or unearthed in areas that indicate a 4th to 6th century AD deposition. The location of the sandy lenses and layers in the Roman Street shops excavation indicates a deposition after the Great Earthquake (May 19, 363), up until the mid-5th century (363-450 AD) (Fiema 1998).

In this scenario reconstruction, the floodwaters would have accumulated upstream above the Bāb as-Sīq, most likely in the village of Elgee (Wādī Mūsā today) due to the torrential rainfall and/or rapid snowmelt. Flows of water would have joined in the main channel(s) to enter the Bāb as-Sīq at levels up to 4 to 6m in depth. Downstream accumulation of discharge would have created a torrent that entered the Sīq (to some degree), but found the northern channels of Wādī al-Mudhlim more suitable for flow. If the channel of Wādī al-Mudhlim 1500-2000 years ago was similar to the channel today, its relatively sediment-free, sandstone channel was superlative for exacerbating accumulating floodwaters. As the water rushed down Wādī al-Maṭāḥa, it would have accelerated from 0.5m/s to 1.1m/s, to jump the confluence at Wādī Mūsā, spreading across upstream, pouring across and down the street, accelerating again to 3.3m/s. This increase in floodwater velocity was probably due to the merging of water rushing through the Sīq, into the outer Sīq and into the primary channel of Wādī Mūsā at the Theater. The fast waters from Wādī al-Maṭāḥa would have been thick with Disi sand, silt, and gravel, merging with torrents flowing though the Sīq that were choked with the beige, yellow, brown, and reddish sands the lower sandstones. These surges would have reached 5 to 8m in depth, and created 50m meanders across Petra's main valley, while the water zig-zagged down the Colonnaded Road leaving boulders, heaps of gravel and pebbles in its path. Everything along the road would have been covered in 2 to 4+ m of clay and silt, jumbled and mixed clay, silt and boulders at first, then grading upward into finer and finer beds of sand, silt and clay as the floodwaters receded.

Petra's everyday activities would have come to a complete standstill. Injuries and destruction would have been widespread and depending on the time of day numerous deaths could have resulted. The evidence is clear and connected, however to better determine its date and span of occurrence further excavation and observation is required. So, why the flood does not appear in local or regional historic records is a mystery, unless it occurred as a function of the great earthquake (363 AD), or occurred so close in time, that it was lost in the blur of devastation. Dams, weirs, and flood diversion structures (Bellwald 2007) may have been so ruined that Petra's community had no means to protect itself from desert downpours. Perhaps the flood occurred within months of the earthquake devastation. It would have taken years for Petra to recover from the earthquake alone, so a torrential downpour occurring the following winter or spring (364 AD) or in the immediate years to follow, is not out of the question.

The value and importance of interdisciplinary research here is obvious; the need to link archaeological expertise, historic research, geographic geomatic work (cartography, remote sensing, and GIS) with geomorphologicial training and observation is paramount. This paper represents a beginning from which more observation, excavation, field research, and archival work may yield further information and clarity on the probability of this disaster – a first step in elucidating the likelihood of a Petra Great Flood between 363 and 450 AD. George Bernard Shaw said it best when he wrote "Science never solves a problem without creating ten more" (1935).

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