QANAT FIR'ŪN – DOCUMENTATION OF THE 100 KILOMETRES AQUEDUCT TUNNEL IN NORTHERN JORDAN

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Summary

Since 2004, the author of this report has been engaged in measuring and documenting a Roman tunnel system in Jordan. The tunnel system is larger than any found previously and extends as an overland aqueduct well into Syria. The region, climate, geology, land use and settlement history have been detailed previously (Döring 2004, 2008, 2009), permitting this report to concentrate on the findings of the excavation.

These indicate that the underground-channel was constructed to supply the Decapolis cities of Abila, Gadara and, probably, Dar'a. Radiocarbon dating has revealed that the main building period was between 90 and 150 AD. The total length of the aqueduct is over 170km, according to current research. There are four tunnels of 1, 11, 34 and 60km respectively and an overland section of 64km. Thus, the aqueduct appears to be the most elaborately constructed long distance pipeline of the Roman period; the underground section of 106km is the longest of Antiquity discovered to date.

Previous Work

In 2004 the author was called in to assess a tunnel beneath the settlement of az-Zayraqūn. The tunnel had been discovered during archaeological work carried out by Tuebingen (Ibrahim and Mittmann 2000) and Wuppertal Universities (Mittmann and Vieweger 2000: 7ff) at the Bronze Age settlement of az-Zayraqūn. The site is located on a tributary of the Yarmouk river, the Wādī ash-Ashallālah (**Fig. 1**), and had hitherto received little attention. Closer investigation quickly revealed that the tunnel was not of Bronze Age date, as had previously been assumed, but was likely to be much more recent. This assumption was based partly on the fact that the tools needed to cut away this amount of hard limestone were not available in the third millennium BC. It was also clear from plaster and sinter traces that a large volume of water had passed through the tunnel for long periods, indicating that it was unlikely to have been a channel for simply local water supply. The tunnel appeared to be part of a larger and hitherto undiscovered aqueduct system (Kerner 2004).

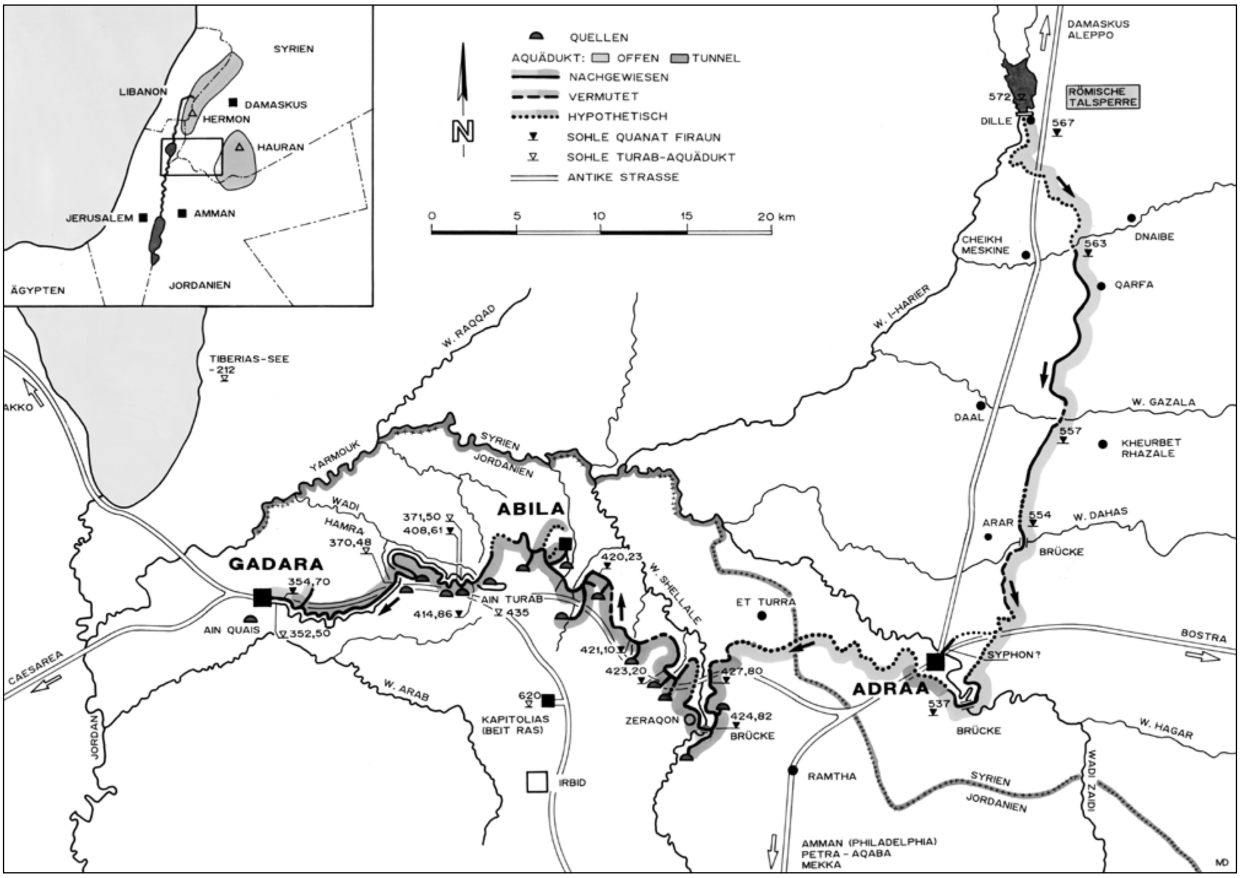
In order to locate the system, a survey of the surrounding area was carried out. Further tunnel sections were discovered which had, to judge from the chisel marks, been dug out using sloping construction shafts in both directions. The shafts, some of which were up to 70m deep, were equipped with steps and mainly blocked up, making them unidentifiable from the surface.

Levels revealed that all tunnel sections lay at the same height. They had been built using the same construction method and appeared to belong together, thus indicating a unified and supra-regional plan. Given that Antique cities which could have used such a water supply were absent in the surrounding area, plus the fact that the origin of the tunnel had not been located, its interpretation as a long-distance pipeline seemed reasonable.

This hypothesis led to the establishment of a project supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, or DFG).

In order to determine the course of the tunnel, the author used topographic maps to plot a possible route in both directions, taking Antique construction techniques into account. This began at Wādī ash-Ashallālah and, with the decline of 1 % which was customary in Roman construction and a maximum depth of 70m, confirmed its interpretation as a long-distance pipeline. The route passed directly by the Decapolis cities of Abila (20km) and Dar'a (40km), ending after 60km at Gadara (**Fig. 1**).

The author and his students made a systematic investigation of the 400 km□area between Wādī ash-Ashallālah and Gadara along the predicted tunnel route (**Fig. 2**), and were surpris-



1. Project area in northern Jordan and southern Syria. The tunnel system in Jordan is more than 100km long; ca. 90 % of this was located and surveyed. Sections marked with •••• were either blocked or flooded.

2. Landscape at al-Mughayyir. The tunnel goes through the top third of the right hand slope at a depth of 20-40m (86.5km).

ingly quick to obtain results.

During the second season, over 30 construction shafts were discovered within a few weeks (**Figs. 3 and 4**). These were the only access points to the tunnel. By the end of the third, 2006, season over 100 open shafts, over 200 blocked shafts and three tunnel sections had been found. Although the tunnel sections did not allow continuous passage from end to end, their total length added up to *ca*. 106km.

The first aim of the 3½ week season in 2007 was to locate the remaining gaps in the tunnel route. This was followed by the survey and measurement of the entire Jordanian section, including taking levels on the tunnel floor. Reference pegs had already been used to mark the openings of significant construction shafts during the 2005 and 2006 seasons.

The length of the aqueduct meant that its survey was only possible using satellite technology (GPS), which also enabled centimetre precision in the measurements. This was necessary because the height of the channel floor at the beginning and end of the tunnel section had an average gradient of only 0.75 % (75cm per km). Therefore, the utmost accuracy was required when measuring the elevation of the tunnel.

Local estimates were then used to tie in the overland reference points with the tunnel floor. Optical measurements proved difficult owing to changes in gradient and curves in the shafts, which sloped at an angle of 45 to 55°. Neither was it possible to position the instrument above the shaft or to change the instrument within the shaft. A manometer with tube was therefore used, which in some cases delivered more accurate results than a frequently re-positioned tachymeter. Check measurements revealed differences of only a few centimetres between the two.

3. Typical construction shaft with steps.

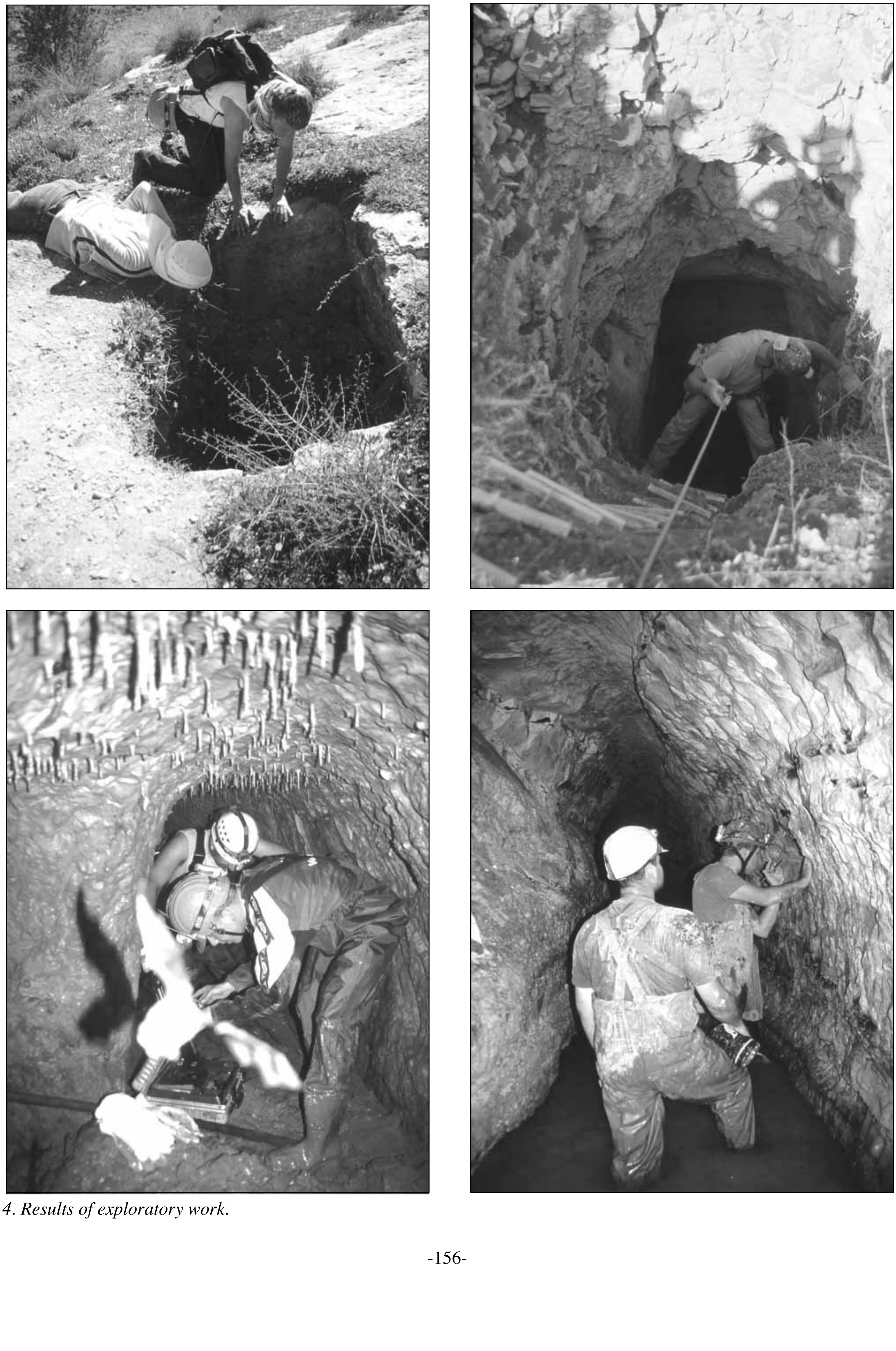
Position measurements had greater tolerance of discrepancies, which did not have such a negative effect on results. Depending on the local setting, a tachymeter or a cross laser with horizontal reference circle were used, whilst a compass was used to check and confirm the results. A constant comparison of measurements revealed differences of only 2-3 % over several hundred metres.

The tunnel was spacious and lined with screed and plaster. Sections of several hundred metres and, in one case, 2 km. permitted unobstructed passage (**Fig. 5**). Occasionally, the previous water level was indicated by sintering. In other sections, where the hewn rock had not been plastered over, construction appeared unfinished. Passage through the tunnel was frequently obstructed by earth that had accumulated below collapsed shafts. This blocked the cross-section of the tunnel, causing rain water to gather behind it. However, hardly any later fissures were discovered. It was not possible to carry out further investigation in the vicinity of the Syrian - Jordanian border and the course of the aqueduct along two short sections at Abila and the spring of 'Ayn Turab remains unclear (**Fig. 1**).

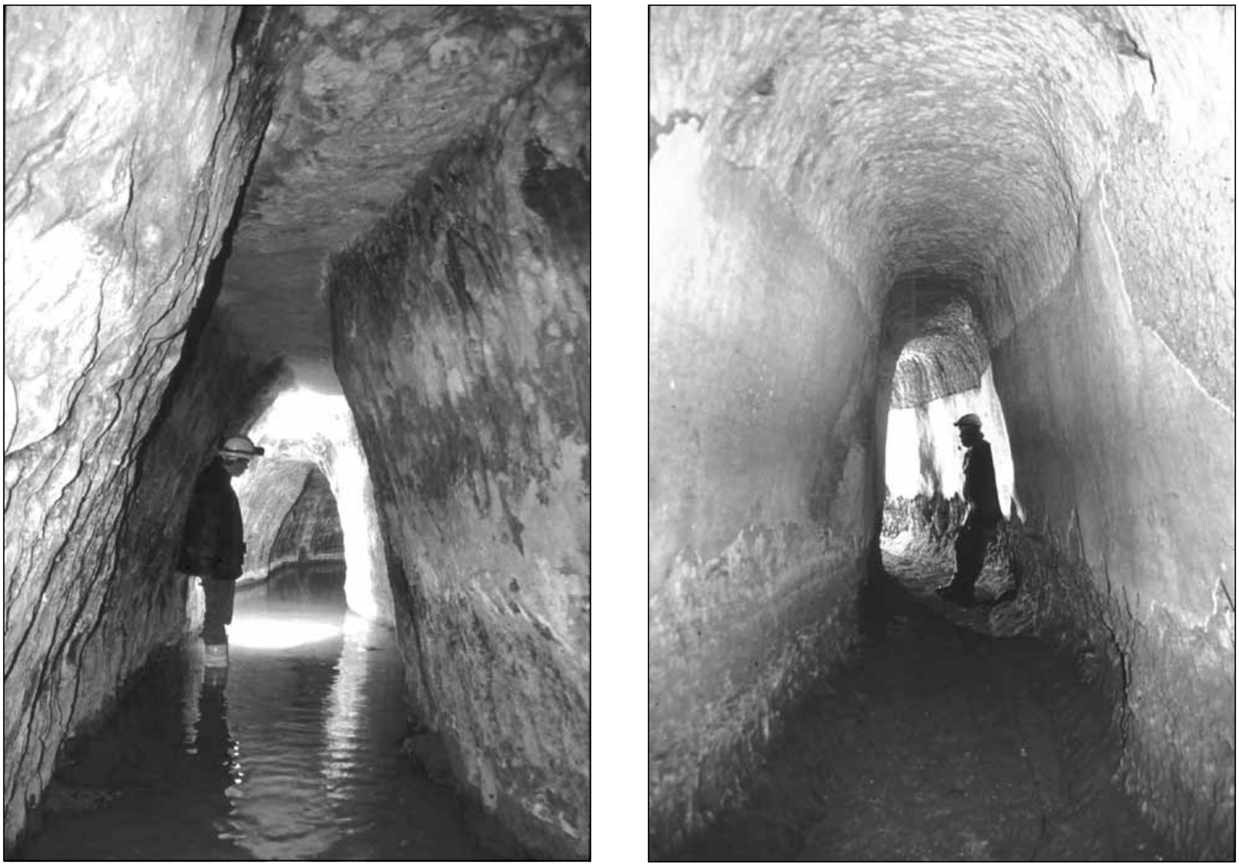
Aqueduct Route

Nineteenth century reports referred to fragments of an Antique aqueduct near the Dar'a - Damascus road, which began at Dille (565m. asl, km. 0) and ended at Dar'a. Remains of this aqueduct are to be found between Dâal, Syria and Dar'a, as well as in the southern part of this town (Buckingham 1825: 167; Wetzstein 1860: 123-125; Schumacher 1889: 49f; 1890: 78f, 162-166; 1897: 125-128; 1915: 136f; Rindfleisch 1898: 13-14, Table 1; Steuernagel 1926: 497f.). Further hypothetical details, deduced from the upper of the two tunnel systems beneath the acropolis at Gadara are provided by Bienert (2004) and Häser (2004).

Only in a later phase does the aqueduct appear to have been extended towards the west. This branch began shortly before Dar'a and crossed the Wadi Zaidi south of the city. Construction became technically more demanding around ash-Shajara (440m asl, 64km from



4. *Results of exploratory work.*

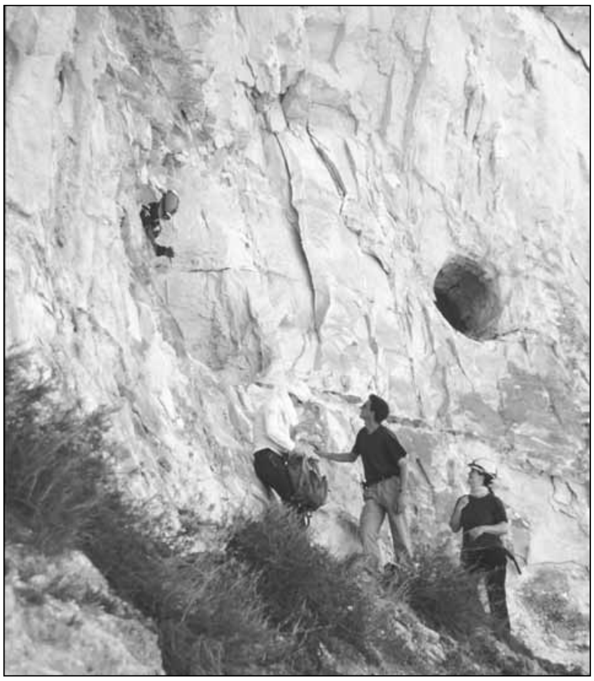


5. *Tunnel: unfinished (left, 149km) and plastered (right, 109.5km).*

Dille). The Wādī ash-Shallālah is almost 200m deep and had to be bypassed near its headwater, as was the norm in Antique aqueducts.

Here the aqueduct entered the first tunnel, one of 11km. After a complicated line through mountain precipices (**Fig. 6**) the spring of 'Ayn Guren (75km) was incorporated and, after another 1km length of tunnel, the valley was traversed with a 20m high and 100m long bridge (424m asl, 76km), now ruined (Döring 2004).

The third tunnel began on the far side of the valley, and continued for 94km as far as Gadara. This headed north along the western side of the Wādī ash-Shallālah, meaning that 40km of tunnelling was required to cross a valley only 800m wide. Abila (122km) was reached after further valleys, in which several springs were utilised as water sources (Fuller 1985: 271, 523ff; Fuller 1987: 250-252, 523-525; Mare 1982; 1986: 129). Further circumventions of valleys (Schumacher 1897: 181 ff) followed until the aqueduct switched to the south side of the Gadara plateau, at 159km, 401m asl below



6. *On the eastern bank of Wādī ash-Shallālah the aqueduct passes through rock walls for an extended distance. The picture shows two construction shafts (72.5km).*

the watershed between the Yarmouk and Wādī al-ʻArab. The aqueduct ended at Gadara (335m asl), approximately 170km from Dille.

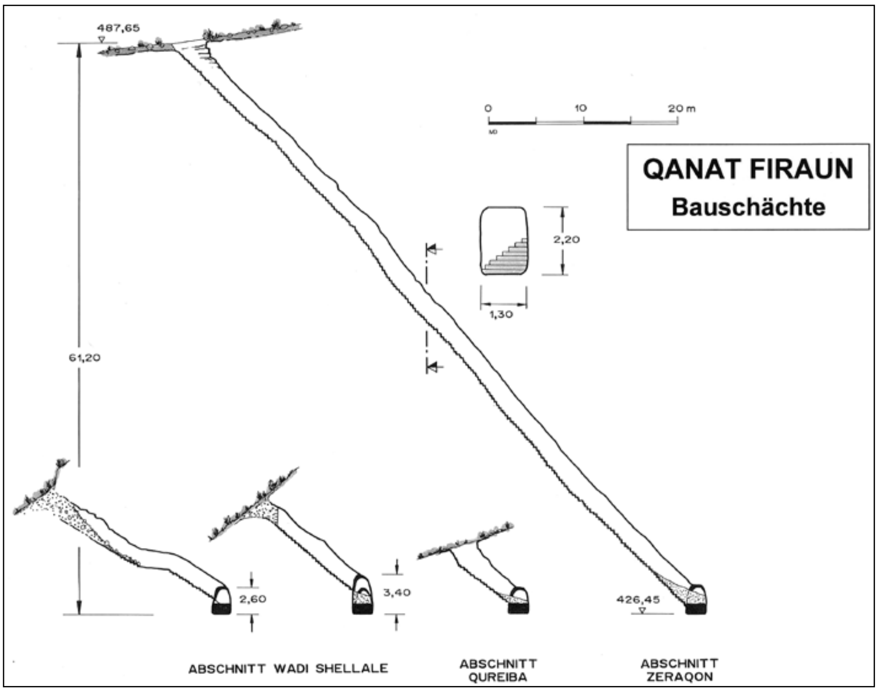
Tunnel Construction

The entire tunnel system was dug out of the limestone bedrock using mining techniques, *viz*. hammer and chisel. The rock is frequently permeated by horizontal flint layers, which occasionally form the tunnel roof. Above-ground measurements and staking out the route were followed by excavation of construction tunnels and shafts. These were spaced at 20 to 50m intervals, with a depth of up to 70m and a width of 1.30m. They were between 1.60 and 2.20m high and usually had a gradient in excess of 45° (**Fig. 7**). Chisel marks (**Fig. 8**) show that tunnelling was carried out from the foot of the shafts in both directions, so that tunnelling teams worked towards one another. It is estimated that the number of construction shafts that were sunk totalled around 2900.

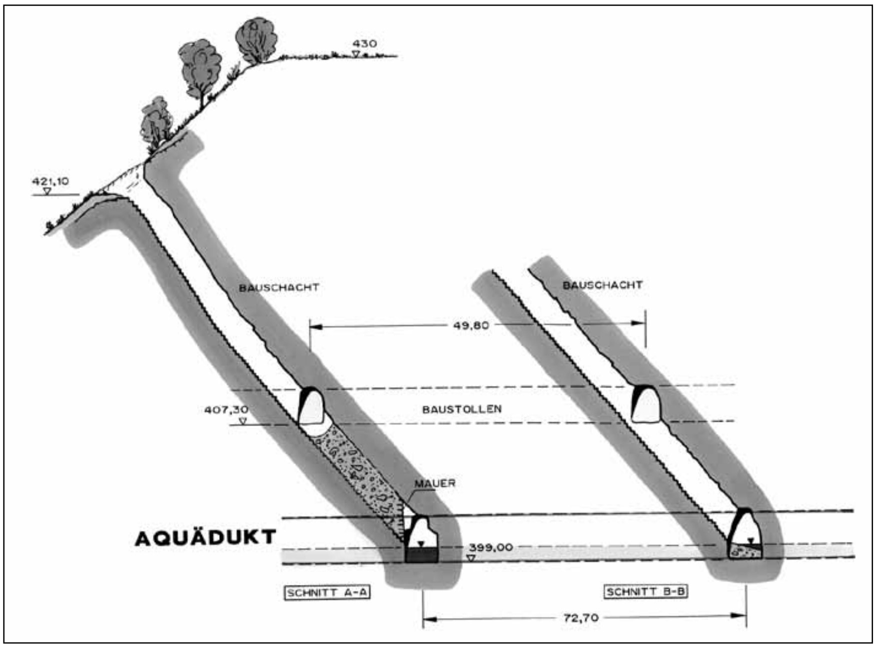
Between 80km and 130 it became clear that the Antique tunnel builders had diverged from the concept that they had initially followed. Rather than constructing the tunnel along valleys that bypass the mountains, the course cut a straight line across plateaus which are several kilometres wide. This required particularly deep

8. Construction shafts with construction tunnels at Al'āl (99km). The lower part of construction shaft A-A is filled with rubble; shaft B-B is thoroughly blocked below the ground surface. Today, access to the aqueduct is provided by shaft A, the pilot tunnel and then shaft B (Section S, **Fig. 7***).*

and, in some cases, multi-level construction shafts (**Figs. 9 and 10**) in which the first sloping construction shaft was followed by a horizontal tunnel and then a second sloping shaft down into the aqueduct. This restricted ventilation of the tunnel, meaning that gas detectors (for O_2, CO_2, H_2S, methane etc.) had to be used during the 2007 survey. When limestone comes into contact with carbon dioxide in air and water it reacts and becomes permeable. Therefore the 1.80 to 5m high and 1.20 to 2.50m wide tun-



7. Construction shafts.



9. The tunnel was excavated using hammer and chisel. This picture shows the marks left by a quadratic single-point threading tool with a diameter of ca. 1cm.

nel here had to be coated with waterproof plaster and supplemented with screed (**Figs. 5 and 11**). In order to make the plaster waterproof, 'hydraulic' material was incorporated into the mortar. This was usually ground tuff or *pozzolana*, a volcanic ash from Puteoli near Naples. If no such 'hydraulic' materials were available, ground charcoal, which has similar properties, could be used instead.

Because orientation was difficult underground, workers began with pilot tunnels set into the tunnel roof. These often curved further into the mountain (**Fig. 12**), which should have led to a breakthrough when the construction tunnels being dug from opposite ends met in the middle. That this was not always the case is reflected in numerous examples (see below). Following the breakthrough between the two tunnels, the full width of the cross section was dug out, differences in direction and height of tunnel were corrected, and the tunnel floor was finished off. As an example of the water level in the tunnel, in a section at Abila the upper traces of sinter are clearly defined and reflect a level of 50 to 80cm. This corresponds to a flow of 500-700 l.s. (40,000-60,000m□per day). The main water source was the now dry dam 60km away at Dille, Syria. At least ten springs fed into the aqueduct during its course and represented an additional source of water.

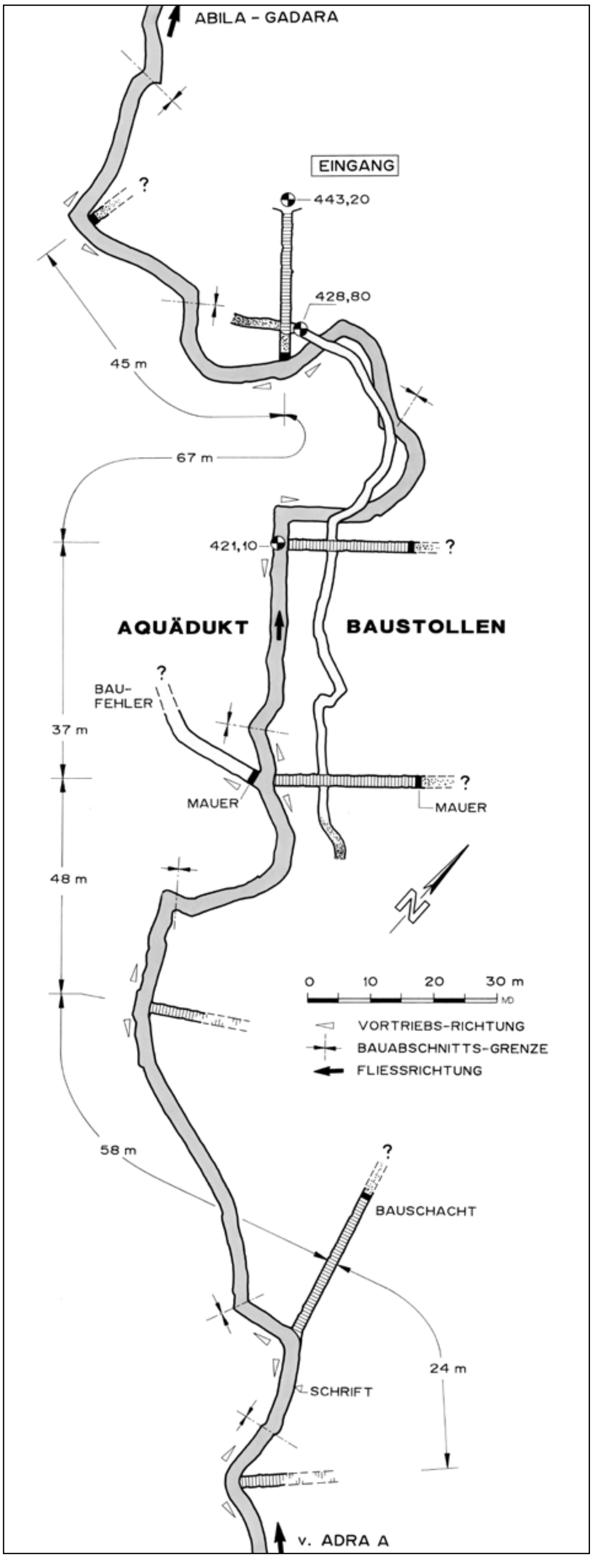
Ancient Measuring and Route Pegging

Specialists who worked all over the Roman Empire would be requisitioned for the general planning and main pegging of the larger aqueducts. The construction would be carried out by local workers and, frequently, military forces. In order to peg out the angle the *dioptre*, an instrument similar to the theodolite, was used. A *chorobates*, or water level about 6 m long, and water level gauge made from goat intestines were used for levelling. Horizontal monitoring was carried out using iron sights, with a plumb-line being used for vertical monitoring.

The landscape between Dille and Shajara was level and without large obstacles (**Fig. 1**), meaning that routing cannot have presented many difficulties. Thus, the pegging out methods normally used for Roman aqueducts could have been applied without complications. The same can be said for the tunnel section running from the watershed of Wādī Ḥamra - Wādī al-'Arab to Gadara, which is not obstructed by valleys.

The section between Wādī ash-Shallālah and the watershed would have been more difficult. Although no reports of the method used are available, topography permits the following hypothetical reconstruction.

The north Jordanian plateau runs steeply down to the Yarmouk, incised by steep valleys.



10. The irregular course of the tunnel course shows how difficult underground orientation must have been. In the middle of the tunnel section, a failed attempt is indicated by (?). This could not be investigated owing to lack of oxygen.

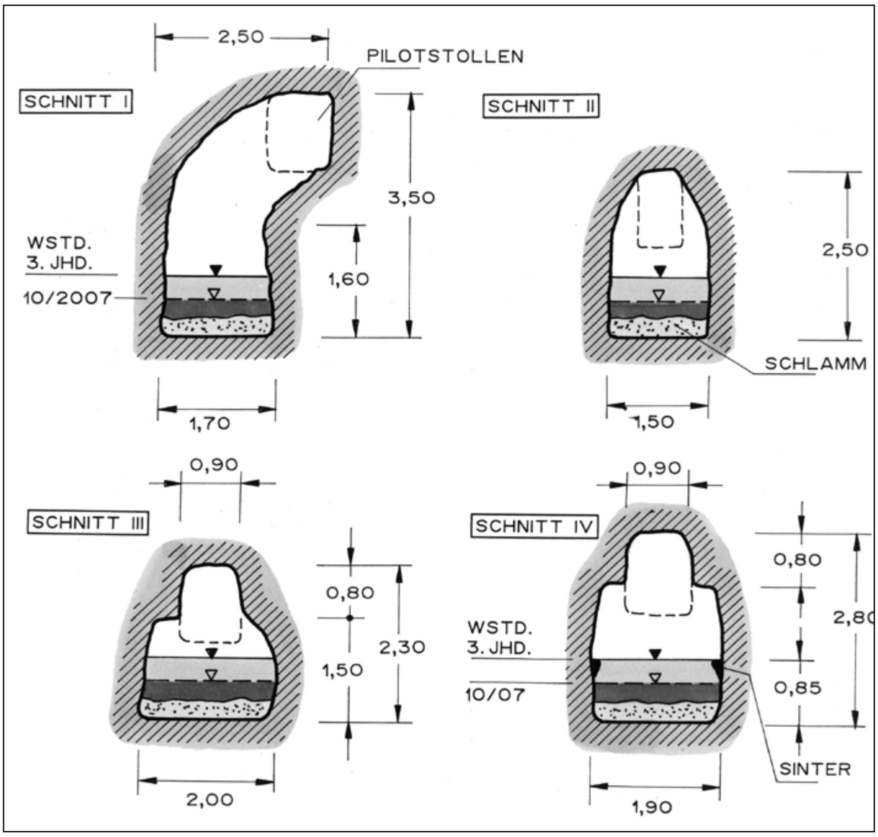
The 'table mountains' to which this has given rise are almost all at elevations of around 400m. asl. The line of sight between mountains is uninterrupted and the distance between them is never more than one kilometre. It is therefore likely that levelling was carried out using two batter boards mounted horizontally, using a *chorobates* or a water level gauge, in relation to fixed points on the opposite mountain ridge. This would have made it possible to work forward from mountain to mountain. The eastern side of Wādī ash-Shallālah lies 40m higher than the western 'table mountains'. With the 1 % decline common in such constructions, circumvention of the valley would require a pipeline of 40km.

Following this, fixed points would have been used to establish the main levelling datum and project it forward into the tributary valleys. The elevation of the route could then be offset from the 'table mountains' at around 400m. asl, although the additional lengths needed to circumvent valleys had to be taken into consideration. If the start points for the construction tunnels were marked with stakes, the tunnel base could be extended into the mountain using water level gauge and plumb-line (**Fig. 13**).

The gradient of the decline is extremely low; averaging just 0.3 %. In the eastern, *ca*. 60 km tunnel section it is 0.1 to 0.9 %, or 10 to 90cm per km. In the middle section the decline is 1.4 to 1.6 % and in the western section *ca*. 2.6 %. Anyone with experience of tunnel construction will know how difficult it is to maintain such a low gradient, even over much shorter distances and with the benefit of modern techniques. However advantageous the sloping construction shafts may have been for spoil removal, they must also have presented an obstacle to the accurate projection of direction and elevation from surface to underground operations. How this was carried out with such precision has yet to be fully explained.

Position Errors

Although frequent checks against the staked route must have been carried out, position errors did occur. Despite the pilot tunnel technique and the limitation of intervals between construction shafts to a maximum of 120m in almost every instance, divergence from the correct route was common. This was partly because the 'curved'



11. Cross-section of the tunnel.

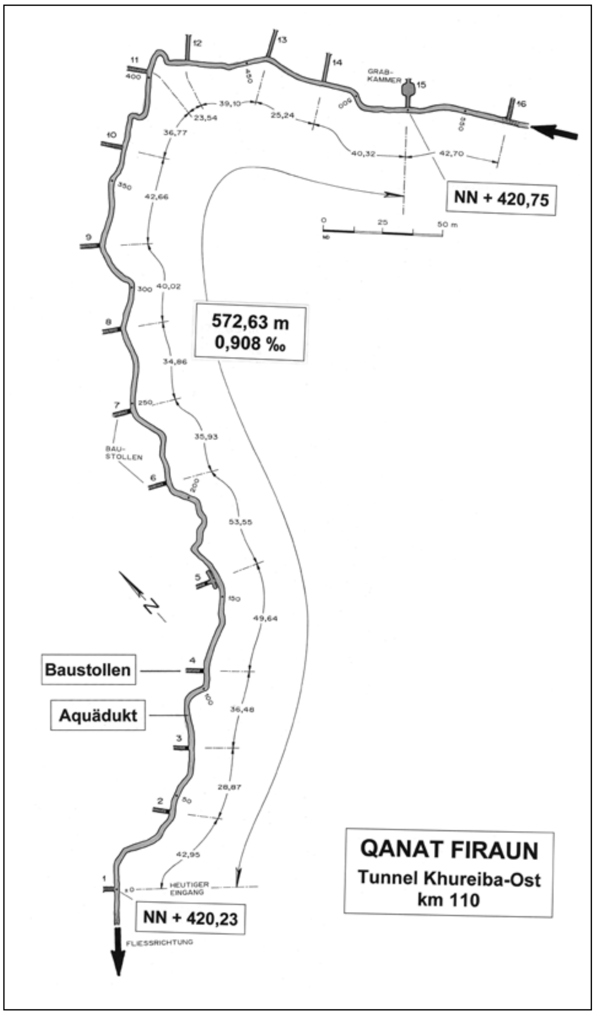
tunnelling technique was not consistently applied or could only be applied with difficulty as, for example, when the route itself curved. As long as the tunnelling teams from opposite sides met at some point, errors could be corrected without great difficulty. When the tunnelling teams passed by one another, completely missing the point of intersection, the situation became more difficult. A more exact measurement usually made connection in the right direction possible. However, at one place in the Wādī Ḥamra a cross cut was made in the wrong direction and had to be corrected by bringing the whole pipeline back into the right direction.

Occasionally, as in the case of az-Zayraqūn (76km, **Fig. 14**), the tunnelling operation had progressed too far for a straightforward solution. In such cases the two sections were connected, not with a right-angled bend, but with an s-bend, probably in an effort to avoid turbulent water flow which could cause an increased build-up of sinter. At the same location, the route had initially been laid too close to the precipitous ground surface. This caused fissures in the rock, which was less stable here. Similar cases were found on the east side of Wādī ash-Shallālah, where the tunnel had been routed too close to the rock face, thus causing entire mountain sides to collapse (**Fig. 15**). These problems were subsequently avoided by setting the tunnel further into the mountain.

Near the 'Ayn Turab spring, a 130^{o} curve was needed to circumvent a valley in which construction shafts could not be dug for an extended distance. A serious error in measurement appears to have arisen here (149km), meaning that the intersection point had to be located by means of a winding 200m 'search' tunnel.

Height Differences

When minor height discrepancies, appearing as offsets of up to 2m in the tunnel roof, arose, the floor of the tunnel could be corrected without difficulty, so that no 'sediment fall' developed and an even water flow was guaranteed. However, in some cases reworking of the tunnel floor was not attempted, for unknown reasons. An example of this, in the form of a 60cm step against the water flow, was found near the 'Ayn Guren spring (74km, **Fig. 1**).



12. *In order to minimise the risk of the two tunnelling teams missing one another at the intersection point, the course of the tunnel curved into the mountain as shown by construction tunnels 6 and 9.*

In some cases, greater differences in height made new construction necessary. This is the case at 70km, where one long tunnel section was replaced by another section set 1.50m higher. Another example is found at Wādī Ḥamra, where the tunnel was excavated with a slope ascending against the water flow for an extended stretch, meaning correction could not be carried out by simply lowering the tunnel floor. Therefore, when the doubled tunnel height had been reached, a second tunnel with the corrected gradient was constructed beneath the first (**Fig. 16**).

Date and Use

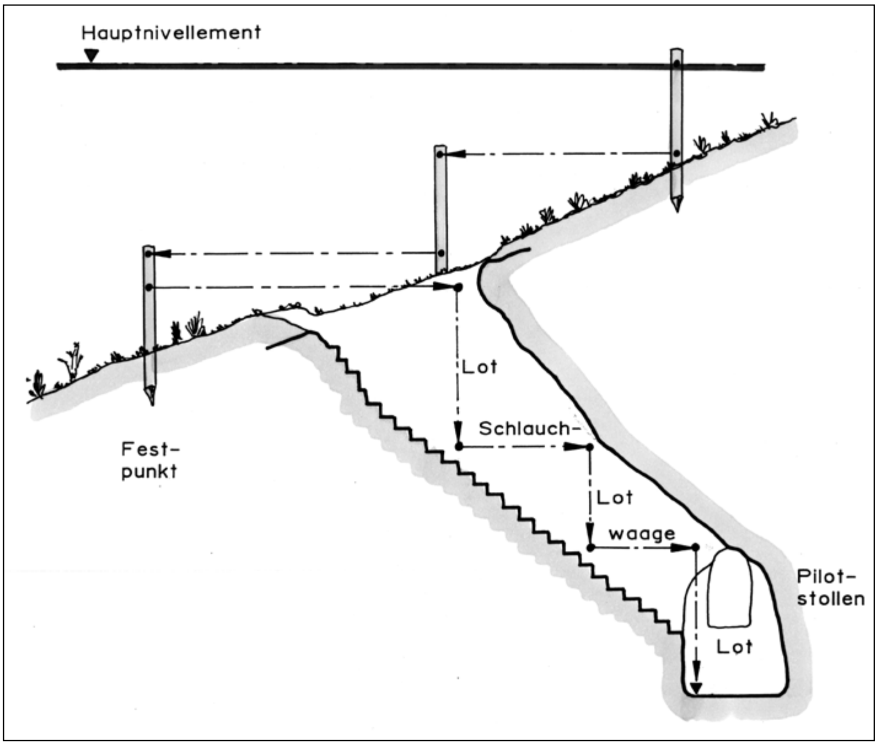
The first, approximate attempt to date the aqueduct was based on sherds found in an incomplete tunnel section in Wādī Ḥamra, which were indicative of the Roman period (63BC. to 5th century AD). A more accurate effort was subsequently made using radiocarbon analysis (^{14}C) of charcoal in the aqueduct waterproofing between Wādī ash-Shallālah and Wādī Ḥamra. This suggested that construction occurred some time between 90 and 210AD, a period when the Decapolis cities enjoyed great prosperity. Sintering between the Wādī ash-Shallālah (75km) and a point west of Abila (116km) indicates that the aqueduct was in use for several centuries. This is agreement with ^{14}C dating that suggests that the plaster at 77km was repaired around 380AD.

The aqueduct's regular operation may have come to an end with the collapse of Byzantine rule in 636AD, or the catastrophic earthquake of the 8th century (Hoffmann 2002). This is suggested by inscriptions found in the tunnel (**Fig. 17**). The route of the pipeline, its cross-section and degree of completion suggest that construction was carried out in the following chronological order:

1. Dille - Dar'a (44km),
2. 'Ayn Rahub spring - Abila (33km),
3. 'Ayn Guren spring – 'Ayn Rahub (12km),
4. Dar'a – 'Ayn Guren spring (32km),
5. Abila – 'Ayn Turab (23km),
6. Watershed - Gadara (12km, unfinished),
7. 'Ayn Turab - watershed (14km, unfinished).

The first sections to be built were clearly — though not necessarily simultaneously — sections 1 and 2, followed by sections 3 and 4 as an extension of section 2, and then section 5. The numerous construction errors in section 6 are likely to be responsible for the fact that this was abandoned before being finished, without plaster or screed coating. Thus, section 7, which was finished before section 6, was not able to hold water and ended up as something of a 'white elephant'.

A few hundred metres west of 'Ayn Turab spring, Qanāt Fir'ūn is higher than the older aqueduct that led from there to Gadara (Weber 1991, 2002: 35; Zens 2006). At this point, which was previously inaccessible, water could have been redirected into the lower pipeline and been carried to the city through this channel.



13. Pegging out the height in a construction tunnel (hypothetical).

Photography credits

All sketches and photos are by the author, unless otherwise indicated.

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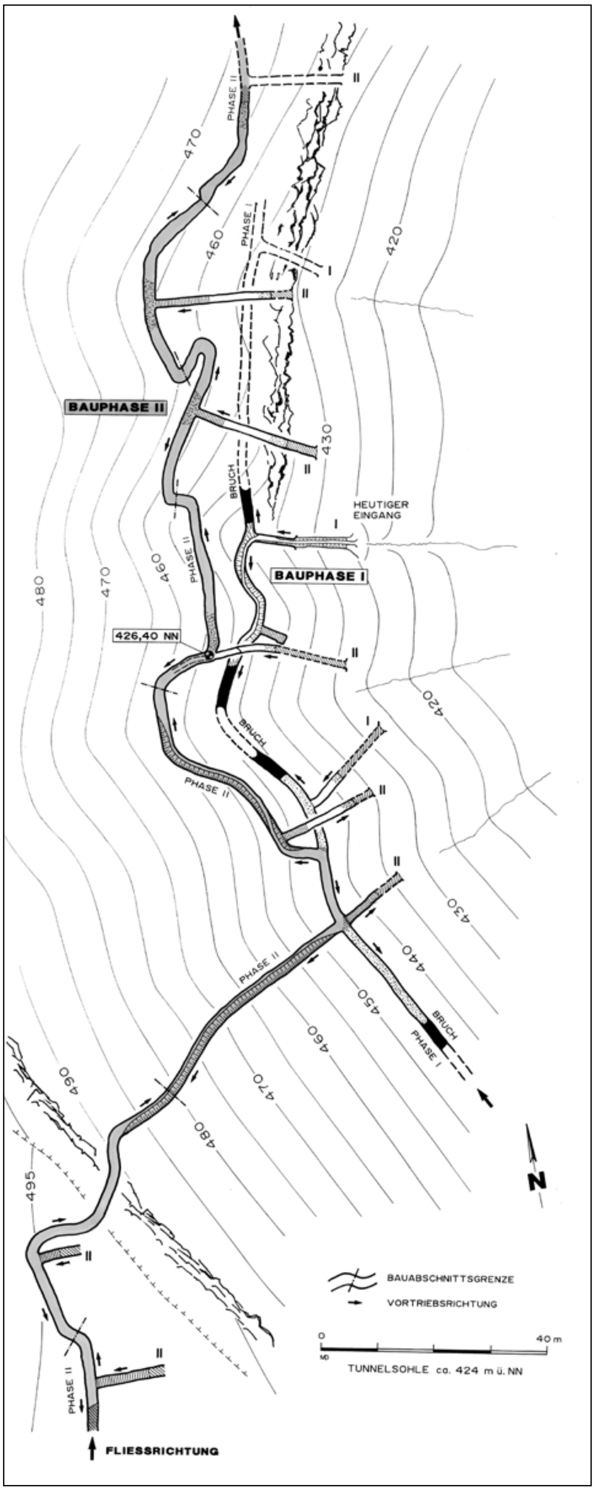
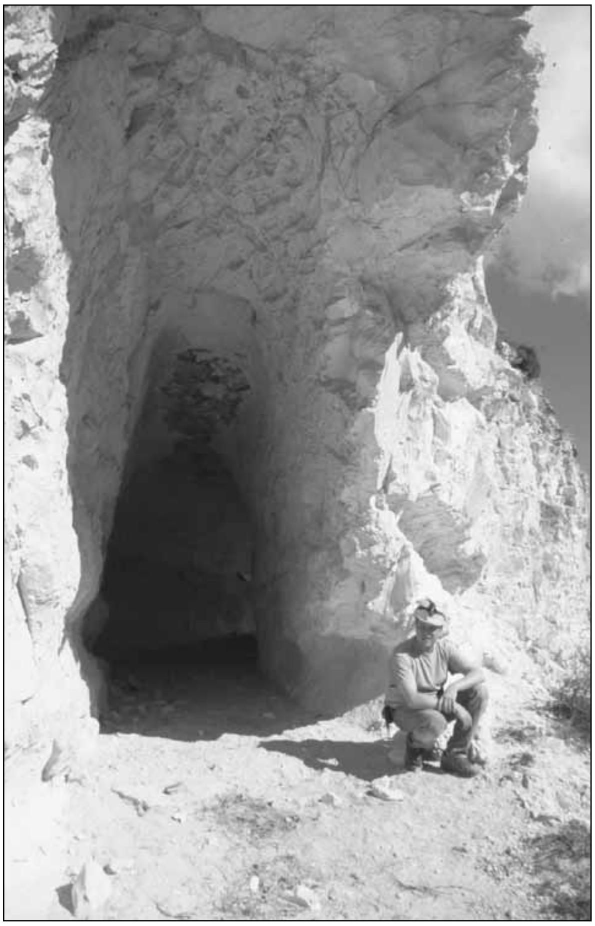


14. Tunnel system with construction errors at az-Zayraqūn in Wādī ash-Shallālah.



15. A landslide caused by tunnel construction exposed the route in Wādī ash-Shallālah.

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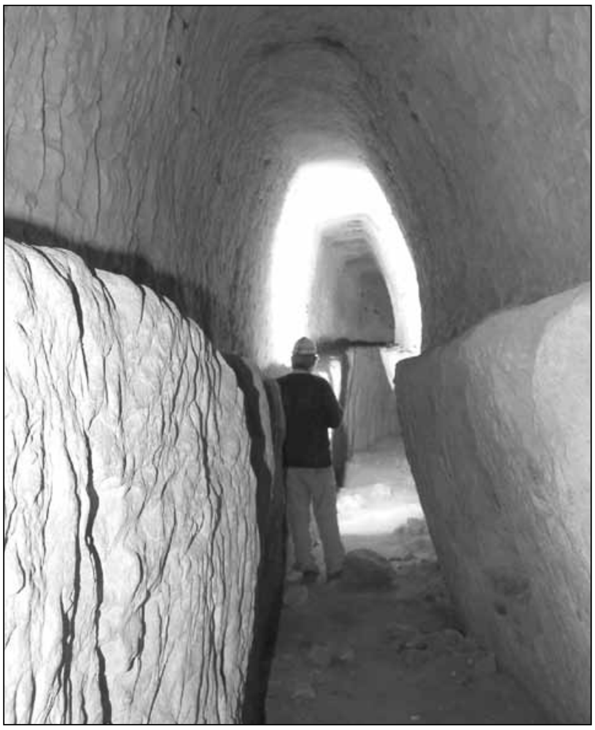
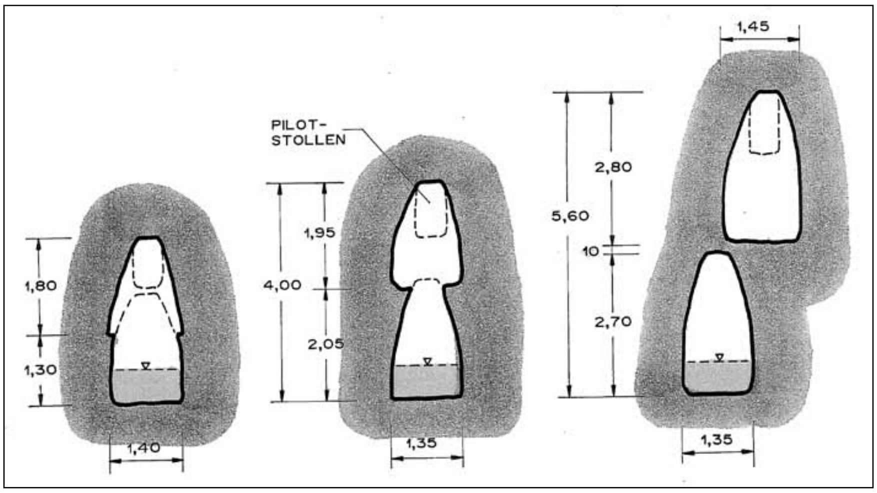


17. Fragments of Greek writing from the tunnel, probably 7th century (Photo: P. Keilholz).



16. A two-level tunnel in Wādī Ḥamra to correct a difference in height.