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Tunnel engineering in the Iron Age: geoarchaeology of the Siloam Tunnel, Jerusalem

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Abstract

The Siloam Tunnel (ST) is the best-identified biblical structure that can be entered today. We use geological, structural, and chemical features of ST and its internal deposits to show that it is an authentic engineering project, without any pre-existing natural conduit that could have guided its excavators. Radiometrically and historically dated to ∼700 BCE, ST pinpoints the technological advance in leveling techniques that was essential for the construction of such a long tunnel without intermediate shafts. A combination of geological and archaeological evidence demonstrates that the circuitous route of ST and the final meeting of the two excavating teams are associated with continuous modifications of the plan to allow acoustic communication between hewers and the surface teams. Hydraulic plaster was applied throughout the tunnel in order to seal voids of dissolution and tectonic origin. Organic material accidentally entrapped in the plaster was carbon 14 dated, and speleothems were dated by U–Th, both corroborating the historic and epigraphic evidence ascribing the engineering advance in tunneling techniques to the Judahite King Hezekiah.

Keywords: Hezekiah Tunnel; Iron Age waterworks; Hydraulic plaster; Siloam Inscription; Gihon Spring; Warren Shaft; ^{14}C dating

1. Introduction

1.1. The Siloam Tunnel

Among ancient techniques, constructing a tunnel between two distant points involves mastering several sophisticated fields, including engineering, architecture, geodesy, hydraulics, and geology. Understanding the methods of construction of ancient tunnels may shed light on early stages of these sciences, since they must have been developed through practical needs. As no ancient text describes the technical principles of tunneling prior to the Roman Period, such a study becomes naturally field-oriented. ST in Ancient Jerusalem (Fig. 1) is unique in the availability of a combination of records associated with its construction: biblical narratives which describe the purpose of the project, backed by Assyrian documentation of the campaign of Sennacherib against Judah; the Siloam Inscription, discovered in the tunnel, depicting the dramatic encounter of two excavating teams; and finally physical and geo-archaeological field evidence [19,24,37,42,51].

ST represents a major advance in tunneling techniques, being a long (533 m) tunnel without man-made intermediate shafts present. Earlier Assyrian tunnels were constructed in short segments between successive intermediate shafts, spaced a few tens of meters apart [9,43,46]. Reducing long tunnels into short segments allowed easy underground connection and ventilation, thus avoiding the need for sophisticated tunneling

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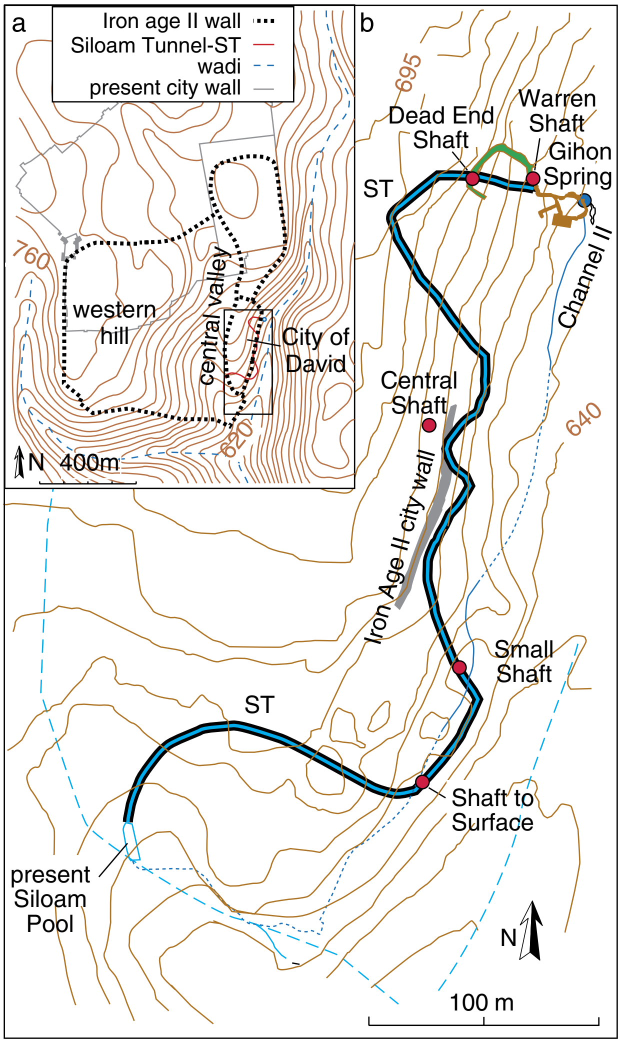

Fig. 1. (a) Map of ancient Jerusalem; contour interval 10 m. (b) The Siloam Tunnel (ST) and associated features in the City of David, ST width is exaggerated; contour interval 5 m.

techniques. In spite of several attempts to understand the tunneling techniques implemented in ST, several major enigmas regarding the tunnel have, until the present, not been resolved: (1) why did the two tunneling teams follow such a twisting circuitous route (533 m) rather than the more obvious straight line course (320 m)? (2) How did two teams following such a complex route manage to meet one another? (3) What is the meaning of '*zdh*' in the Siloam Inscription and what is its significance for understanding the meeting method?

One of the most interesting, and widely accepted solutions offered in the past is termed here 'the karst hypothesis' (KH). It was originally proposed by Sully, an English architect who never visited ST, who wrote: "Since those who have inspected the tunnel mention a cleft in the rock at the point where the excavators met, it seems to me that this cleft is the explanation of the course taken by the excavators in forming this tunnel. Probably the cleft extended from the Virgin's Fountain (Gihon Spring) to the Pool of Siloam, and a small quantity of water would at times trickle through" [53]. This rationale appealed to many others [1–4,26,27,30,31] because it seemed to solve the above-mentioned enigmas with one simple theory. In a well-known publication in the journal 'Science' Gill [27] expanded KH and concluded that ST (as well as other waterworks beneath ancient Jerusalem) 'was fashioned essentially by skillful enlargement of natural (karstic) dissolution channels'. If true, KH implies that ST is not a special technical achievement, but rather an elegant adaptation of a natural feature.

Subsequent observations have questioned KH [22,44,51], but did not present a comprehensive study, as pointed out in a recent review: "A comprehensive explanation of the way the tunnel was planned and cut is still a desideratum" [44]. In the present study we focus our research where scientific techniques permit a detailed analysis of the technical background of ST. In a preliminary study [23] we used radiometric dating of natural (flowstone) and man-made (plaster) materials in ST to constrain the time of its construction, and redefine its relation with the biblical narrative and the Siloam Inscription. Here we use geological techniques to study the plasters and sediments deposited within the tunnel, in addition to its structural geology, morphology, and hewing anomalies, in order to clarify its natural vs. man-made features. Finally, we compare the collected data with evidence from natural karst features from Jerusalem and vicinity in order to test KH. An integration of the new data enables us to elucidate the nature and significance of the technological advance manifested by ST.

1.2. Geology and the regional karst system

ST was excavated within limestones of the Bi'na Formation of Turonian age [26]. In Jerusalem, the formation is generally thickly bedded, gently dipping toward the SE and frequently karstified, as exemplified in the immediate area of the Gihon Spring itself. The spring used to ebb and flow in the past — a property characteristic of karst springs. ST was hewn in the upper part of the Mizzi Ahmar unit, which is massive to well bedded, stromatolithic and frequently pinkish in color.

We have performed a comprehensive study of karst caves in and around Jerusalem, comprising over 1000 caves in the Bi'na formation [14,18,20,21]. The caves can be classified into three groups: (1) vadose shafts; (2) maze caves; and (3) chamber caves. The vadose shafts formed in the unsaturated zone; they resemble vertical cylinders in shape, tapering upward into a fissure. While active, such shafts act as vertical conduits carrying vadose water down, towards the regional watertable. In the studied region, individual shafts are commonly some tens of meters deep.

Maze and chamber caves in the area formed below the regional watertable, under confined and unconfined conditions, respectively, and have smooth curvilinear walls typical of slow-moving water [21,36,52]. A few of these caves reach a total length of several hundred meters up to several kilometers. The maze caves are networks of interconnected narrow passages, most of which developed preferentially along the intersection of a bedding plane and a vertical fracture. These structural discontinuities are consistently observed along the walls and ceilings of cave passages. Chamber caves consist of a void whose width dimension is close to its length. They also form along structural discontinuities, which are observed along their walls. Structural discontinuities are essential for the incipient stage of cave formation in compact limestones, as the water can initially flow only along such hydraulically conductive fissures [33,39]. Such structural discontinuities appear along all karst passages in the studied region.

2. Methods

With the above evidence in mind, a systematic study of large and small morphological features including joints, fractures and voids within and near ST was carried out. All features were carefully surveyed in relation to the three-dimensional morphology of ST and the surface topography (Figs. 1–3), using a Brunton compass and Disto electronic distance measuring device.

We drilled the sedimentary and man-made materials within ST, and studied the core samples utilizing standard petrographic (microscopic), geochemical, scanning electron microscope (SEM), and X-ray diffraction methods (all performed at the Geological Survey of Israel laboratories). Based on these data, combined with stratigraphic relations and previously done ^{14}C and U–Th dating, a detailed classification of the secondary materials in ST was carried out.

3. Results

3.1. Geological structure

We found several mostly small, isolated karst voids, mainly at the southern segments of ST, but no evidence of a continuous karst conduit anywhere along the tunnel. A vadose shaft forms the vertical segment of the Warren Shaft system close to the start of ST (Fig. 1) and a similar vertical void, with smooth walls, projects almost above the Gihon Spring. Four small shafts or kamenitzas [17] are exposed on the rock surface almost directly above ST (Figs. 1–3), serving as local drain of rainfall into the epikarst. From north to south they comprise the (a) Dead End Shaft, (b) Central Shaft, (c) Small Shaft and the (d) Shaft to Surface. Of these, the Dead End Shaft terminates about 3 m above ST whereas only the 'Shaft to Surface' is actually cut by ST. Two major shifts in route direction and a number of minor ones are evident close to these features. This indicates that the dissolution shafts may have played a role as deep tapping points of the surface team, for acoustic communication directing the excavating teams (below).

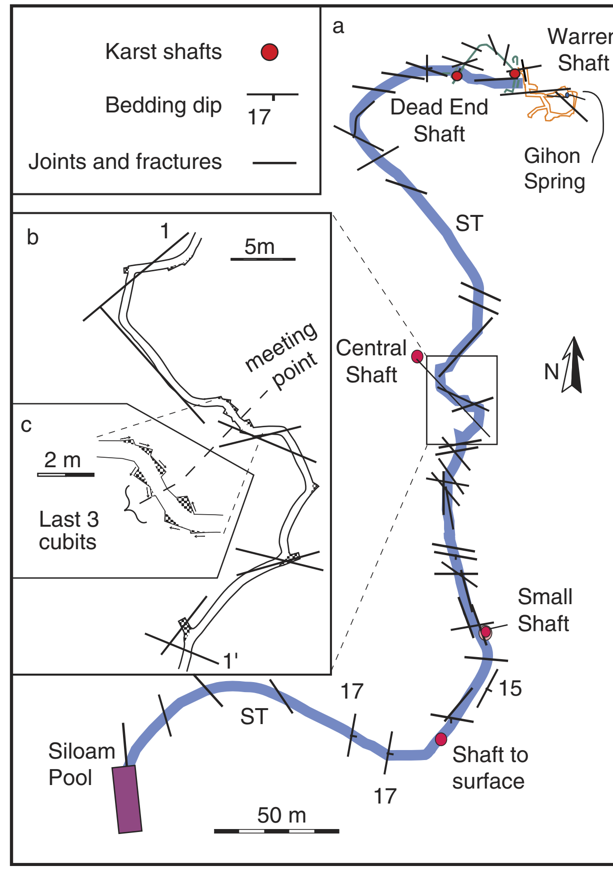

Fig. 3. A plan view of the structural geology and man-made peculiarities of ST. (a) Main structural features, ST width is exaggerated. (b) The central portion of ST; deviations and false starts are grey. (c) The meeting point, hewing directions, and the associated deviations of both excavating teams.

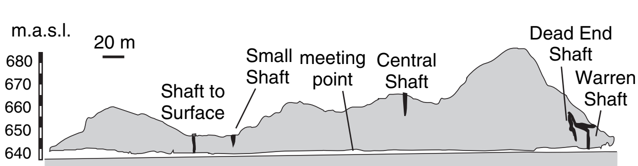

Fig. 2. Profile of ST with its overlying features. The depth of the 'Small Shaft' and the 'Central Shaft' is conjectural, as they are currently blocked.

Gill [26,27] suggested that an original karst conduit was followed and totally obliterated by subsequent hewing. Our survey of many kilometers-long cave passages around Jerusalem [14,18,20,21] shows that the cross section varies significantly along each passage. In addition, the mean width of the passages and the local chambers is larger than ST width. Therefore total obliteration of a karst conduit by the narrow ST (~50–60 cm in width) is virtually impossible.

Fig. 3 shows the orientations of fractures and bedding planes which we measured on the walls and ceiling of ST. Significantly, ST cuts across most fractures at a high angle. Locally the tunnel parallels a few fractures which helped the hewing, whenever advantageous. Along ST such fracture-parallel courses are brief since most fractures either extend in the wrong direction (Fig. 3) or are continuous for short distances only. Bedding planes are rare and appear only along the southernmost portion where ST cuts across a number of ESE dipping beds, only a few with karst-dissolution characteristics. As explained above, a karst conduit of any significant length cannot form unless a structural discontinuity exists along its course. If KH is correct, continuous structural guiding features (fractures and/or bedding planes) would be observed along ST walls or ceiling, since hewing cannot erase their traces; this, however, is not the case in ST.

3.2. Secondary materials within ST

The floor and part of the walls and ceiling of ST are covered by secondary materials, both man-made and natural (Fig. 4). They are important for dating purposes and for understanding the relation between natural and artificial voids. Plaster is the most common of these materials, as noted already by early researchers [8,55] but disregarded by later studies. Plastering of ancient waterworks has been a common technological practice in the region at least since the Iron Age [5,54]. In the present case, the plaster was applied on the floors and walls of ST, at least to chest height, in order to seal these surfaces against water loss through fissures and karst voids. Similar fissures in the bedrock above ST allow dripping water to enter some segments of the tunnel and deposit calcite speleothems, such as flowstone and stalactites.

We distinguish four varieties of plaster with distinctly different petrographic and chemical characteristics which exemplify increasing sophistication in manufacturing technologies with time.

(1) *The ancient plaster* (AP) is the oldest and most important in the present study. AP is a very fine grained hydraulic plaster, composed mainly of a mixture of recarbonated lime (CaO) with small amounts of finely crushed filler materials including soil aggregates, chips of marl and crushed bones, as well as small amounts of charcoal and ceramic shards. Shrinkage cracks and oval vugs are abundant and most are now filled with acicular crystals of carbonates. Besides the dominant calcite phase, XRD also reveals the presence of aragonite, apatite, and traces of vaterite. Many minute, frequently zoned

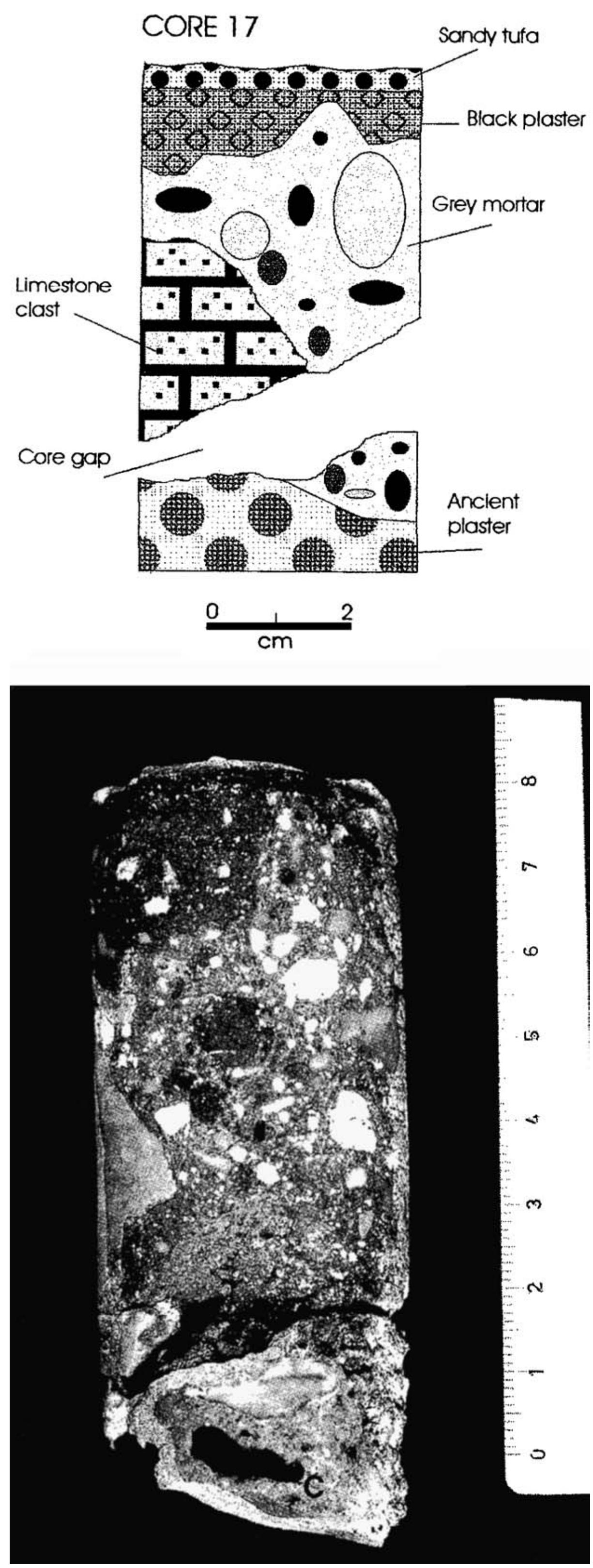

Fig. 4. Typical drill core of ST plasters: heterogeneous grey mortar covering the paler and finer grained ancient plaster which contains a charcoal fragment (black), carbon 14 dated to Iron Age II [23].

isotropic peloids are revealed by SEM to be amorphous varieties of CaAl-silicates. The high contents of P, Cu and Zn and the relatively low contents of Mg, Fe and Al (Fig. 5), as well as the lack of additives such as pottery chips and slag, clearly set the AP apart from the younger plasters in the waterworks. The chemical and petrographic characteristics of AP indicate that the source rock for lime manufacture was the phosphorus-rich marly chalk, which characterizes the Senonian formations cropping out east of Jerusalem. The marly and organic-rich nature of this chalk imparted upon the plaster its natural hydraulic characteristics making it water-resistant. AP dating is discussed below.

(2) *Red plaster and mortar*: besides the lime binder abundant red pottery chips and lesser amounts of rock chips and wood ash were added as filler material into this plaster. The plaster occurs in particular in the area of the southern exit of ST where a church was constructed during the Byzantine period, and also comprises parts of one of the blocking walls east of the Gihon Spring. The abundance of pottery shards indicates that this plaster is Byzantine or younger in age [41].

(3) *Grey plaster and mortar*: this plaster overlies AP. In contrast to the above it is dark colored and has a coarse fabric due to the addition of coarse filler materials including rock fragments, charred wood, ash, high-temperature slag and soil. This variety, which resembles modern concrete, is found almost exclusively covering the AP close to the Gihon Spring. ^{14}C dating has shown that this plaster can be ascribed to the Mameluke period, 1250–1516 CE [23].

(4) *Black plaster*: very fine grained, containing an abundance of materials such as slag, ash and other organic additives. It was applied by the Parker–Vincent expedition [55] as they completed their work in the subterranean tunnels. In major part it comprises the construction material of the blocking walls which cut off the base of Warren Shaft from ST and two nearby channels.

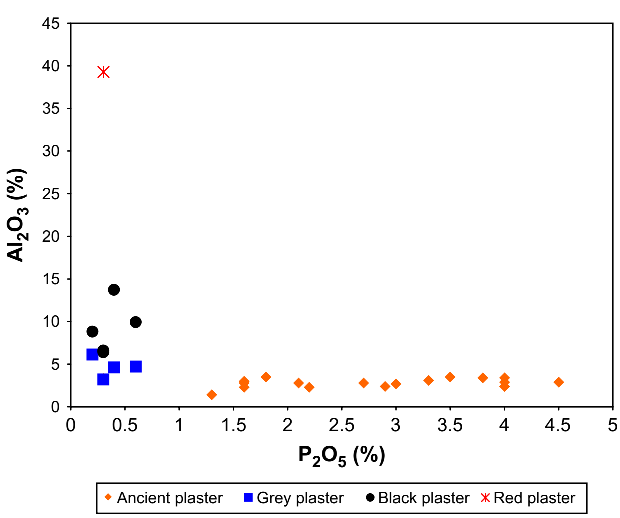

Fig. 5. Siloam Tunnel plasters: two-element binary plot for the elements aluminum (shown as Al_2O_3) and phosphate (P_2O_5) reveals some of the compositional differences in plasters from four different periods in time. The "ancient plaster", dated to the Iron Age II period is typically characterized by a high content of phosphorus. Red plaster is of Byzantine age or younger; grey plaster is dated to the Mameluke period; black plaster is of the early 20th century.

The AP and overlying younger plasters are, in particular along tunnel floors, covered by a continuous ca. 2–4 cm thick lamina of naturally deposited geological materials, namely calcite tufa, silty tufa and siltstone, all deposited from water flowing along ST (Figs. 4 and 6). The siltstone is quartzose but also contains some feldspar and abundant heavy minerals such as magnetite, ilmenite, amphibole, garnet and zircon. This material was probably derived by erosion of a sandy unit intercalated within the limestones of the Bi'na Formation.

We observe that the natural deposits of flowstone, tufa and siltstone along the floor and wall of ST were all deposited *above* AP. Even where plaster is not seen along ST walls, it is frequently found preserved beneath these natural sediments. Our drill cores, however, reveal that no such natural deposits are present *beneath* AP which covers the tunnel floor. Had KH been true, such deposits should be present *beneath* AP, since these sediments are being continuously deposited from the waters of the spring. In addition, the latter observation also indicates that AP must have been applied soon after completion of ST, certainly before sedimentation processes along ST became significant.

3.3. Dating ST

Here we discuss the main issues of our radiometric dating of ST [23], related to the present study. Since the location and morphology of ST closely conforms the biblical narrative, the importance of its age cannot be overstated. This is particularly so, since a group of scholars have argued that most of the biblical description of Israel's ancient history is not much more than an elaborate assemblage of tales cooked up by the priestly sectors of Jerusalem after the return from Babylonian exile in the late 6th century BCE [13,38]. Most researchers attributed ST to the Judahite King Hezekiah (727–698 BCE) based on the biblical narrative (2 Kings 20:20 and 2 Chronicles 32:3,4,30), but arguments against such a link, and date of the tunnel, have also been presented [10,45].

Dating ST is also important when trying to relate it to water-supply technology of the ancient world. Although direct dating of an empty void is virtually impossible, we

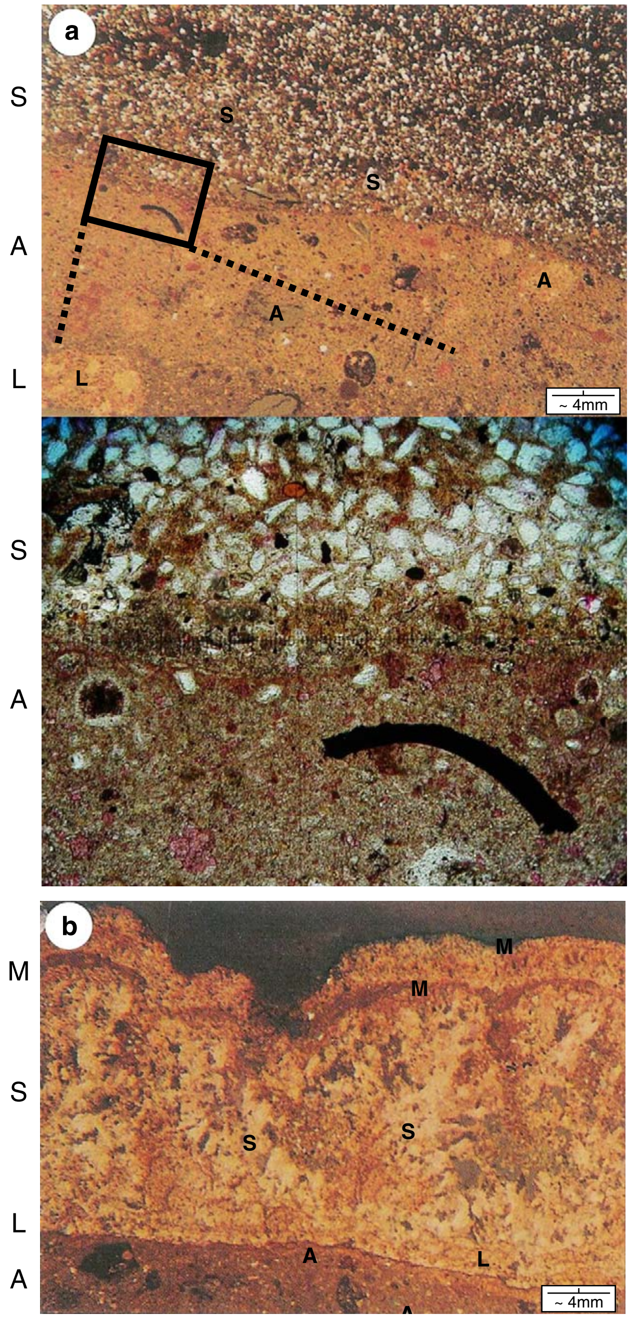

Fig. 6. Photomicrograph under partially crossed polarizers at the contact between the ancient plaster (A) and natural deposits found above it. (a) Quartzose siltstone (S) – detrital deposit of the Gihon waters, composed mostly of angular to subangular quartz and some feldspars (both colorless), iron oxides (opaque grains) and rare tourmaline and garnet (green and brown constituents). Underneath is the ancient plaster (A), consisting mostly of fine recarbonated, somewhat marly, lime binder (buff colored) mixed with small chalk fragments (L), clays, fine potsherds, burnt organic materials (black), chips of bone and foraminifera (seen under higher magnification). The enlarged segment of (a) is under plain light. (b) Ancient plaster (A) overlain by chemical deposits of the Gihon waters, consisting of calcite tufa with finely laminated micritic layer (L), coarsely crystalline calcite spar (S), Mn-rich dark lamina (M), and a peloidal upper free surface.

can date some materials formed within the voids, trying to relate them to the cavity and in this manner constrain its age [48]. During our attempts to understand the construction technique and age of the tunnel we have, as described above, carefully sampled and studied all the relevant materials available in ST. We have discovered well-preserved organic materials in AP, and subsequently together with natural speleothems, were able to radiometrically constrain ST age [23].

The U–Th age of a speleothem, deposited within ST is 317 ± 18 yr BCE; younger ages were obtained for other speleothems in similar locations within ST. Since these flowstones were deposited over the AP and over the artificially hewn surface, they must postdate ST construction and plastering, and provide its minimum age. The calibrated carbon 14 age of organic materials in AP is 822–796 BCE for a piece of wood, and two ranges of 790–760 and 690–540 BCE for a short-lived plant. These materials, both incorporated into AP during its manufacture, must have lived shortly before ST construction. The dates constrain the age of tunnel construction well within Iron Age II, an age which is furthermore sustained by the paleography and philology of the Siloam Inscription [10,25,28,47].

4. ST construction features

4.1. The central portion of ST

The Siloam Inscription and field evidence in the central portion of ST contain the most important indications pertaining to the meeting of the two teams and the way it was achieved; consequently we start the detailed discussion in this segment. The central portion of ST is defined here as the segment between 30 m upstream (northward) and downstream (southward) of the meeting point. The hewing marks, deviations and false starts clearly indicate the meeting point of the two teams [55], leaving no room for doubt regarding its exact location, although this was questioned in the past [12].

At 30 m (distances in this section relate to the meeting point), the north and south excavating teams were progressing in virtually parallel directions (Fig. 3), the north team toward the SSW and the south team toward the NNE. From the 28 m points (1 and 1′ in Fig. 3b) both teams started changing the hewing direction recurrently, in apparent trial and error, with several hewing deviations and false starts (where hewing in one direction was abandoned for another). The southern team abandoned two 0.5–1 m long false starts, while the false starts of the northern team are smaller. Close observation of the headward face of bedrock in the false starts shows no evidence of a karst conduit which could guide the hewers for any distance. Rather, the false starts, as well as the main tunnel, are cut into solid rock. If KH was factual, the route would be continuous and false starts should not be present. As noted above, several small fissures were followed locally by the excavators for no more than a few meters along the tunnel [35]. These fissures may be responsible for trends of some tunnel segments, and thus the erratic behavior of parts of the tunnel (Fig. 3b). As the teams approached one another and mutual subsurface sound communication was finally being established, the hewing directions reveal increasing frequency of fluctuation.

The Siloam Inscription, found emplaced in the wall some 6 m from ST southern terminus, celebrates the dramatic meeting of the two teams after sound communication between them was established from a distance of three cubits (~1.4 m, Fig. 3c): "while three cubits [remained yet] to be bored [through, there was heard] the voice of a man calling his fellow, '*ky*' there was a '*zdh*' in the rock on the right hand and on [the left hand]". The three cubits distance for mutual sound communication is incompatible with KH, which would allow hearing from a far greater distance and leave no room for celebrations. The word '*zdh*' has been interpreted in several ways [11,25], most common of which is a karstified fissure [2,3], but this assumption is not supported by other Hebrew texts. Following Bin Nun [6] we suggest that the simplest explanation for the word '*zdh*' is the feminine of the biblical word '*zd*' (singular – Proverbia 21:24, plural – Psalms 119:21,51,69,78,85,122) meaning evil or wrong. Within the context of the Siloam Inscription '*zdh*' probably refers to wrong (evil) echoes of sound communication responsible for the hewing deviations and false starts. The '*zdh*' *on the right and left*, and associated with *a man calling his fellow*, clearly points to the acoustic problem of recognizing the precise direction of sound origin, with echoes alternating from the left and right. We suggest that the false starts, deviations, and '*zdh*' in the inscription, record the excitement and confusion of the excavators as subsurface communication was dramatically being established. As the inscription infers, the teams could hear each other well only as of the last three cubits, the more distal corrections therefore required different control. Our acoustic experiments between surface and the central portion of ST demonstrate that tapping with a hammer on bedrock is well effective to depths of about 15 m, and detectable up to about 20–25 m. It is unequivocal that the chaotic excavation along the central portion of ST was not fracture, or karst conduit controlled, but can be attributed to the difficult nature of acoustic communication between the approaching, and surface-control teams. Combined with the structural observations above, it is clear that KH can be rejected. In addition, it can also be assumed that the subsurface teams were out of *effective* mutual acoustic range until a few meters of each other, as noted on the Siloam Inscription. Prior to this, acoustic messages from the surface must have been the dominant technique which controlled the complex proceedings underneath.

4.2. The southern portion of ST

The circuitous northern and southern portions of ST appear to be anomalous, redundant and require explanation if, as we have shown above, KH is discarded. One can ask if the hewing in these early directions was made by intent or is it an expression of rushed, poor planning which eventually required modification as new physical and/or geopolitical realities materialized with time.

Throughout most of ST the height from floor to ceiling ranges from 1.3 to 1.8 m. Along the southernmost 52 m, however, the ceiling is up to 5.3 m high, with a mean height of 5 m (Fig. 2). The hewing marks and deviations of the direction show that the upper part of the tunnel (at the present ceiling) was excavated initially, and only later was it deepened to the present floor level. Thus the original southern portion floor was 3–4 m higher than that of the northern portion. Such an error could prevent the meeting of the two teams, and had they met, no water would flow along such a rising gradient. Between 52 and 86 m the ceiling, as well as the original floor, gradually descend eastwards, reaching the correct level 86 m from the starting point. The hewers had to deepen the southernmost 86 m of ST by up to 4 m – removing an extra 320 metric tons of rock to allow the flow of water along a gentle gradient towards the southern exit. The correct level at 86 m was attained by the south team a long time before encounter with the north team, consequently water flow along ST could not have been used for leveling guidance. This suggests that the final elevation was achieved by some kind of a leveling technique, using liquid (water or oil) in a small container and/or in the existing channel II (Fig. 1b). The high degree of geodetic leveling accomplishment is manifested at the junction, where the difference in ceiling elevation between the two teams is only 30 cm.

The southernmost 5 m of ST was hewn along a strongly karstified fracture striking NNE (020°). Alas, the effort to follow this fracture was soon abandoned since the fracture swings gently towards the NNW, and ST hewers by now preferred the NNE (030°) direction, towards the Gihon Spring. This direction was soon abandoned as the overburden exceeded 20 m, probably because sound communication with the surface team became futile. ST now swings first toward the E, and then ESE towards an area of shallower overburden and the Shaft to Surface. Four meters south of the Shaft to Surface the tunnel turns by 45° into an NE direction, cutting through the shaft and continuing NE (Fig. 3a). Hewing marks on the walls show that the Shaft to Surface, although assumed to be used as a beacon, was *not* used as a conventional intermediate shaft for descending from the surface and excavating in both directions, a common practice in other water tunnels (below).

The excavators then followed a ceiling-parallel fracture toward the NE but were apparently directed toward the NNW as they approached the area beneath the Small Shaft. A number of ceiling fractures were thereafter followed for the next 80 m toward NNW and then N.

The route of the southern portion of ST conforms generally with the surface contours (Fig. 1b). We conclude that the incipient NNE direction was initially meant to lead straight to the Gihon Spring. However, when sound communication between the excavators and surface guiding team became futile, tunnel engineers must have realized that lacking good communication, encounter between two teams beneath the middle of the hill would be unattainable. The southern team was then directed towards the area of relatively shallow overburden where acoustic communication with the surface was feasible. In addition, heading towards the unbuilt eastern area of the hill was important for better sound communication. Here, parallel to the Iron Age II city wall that runs at mid-slope [49], a series of rocky terraces conveniently exposed at the time of ST construction descend steeply eastward (Fig. 1b). This area allowed for a certain degree of safety (against breaking the surface) in addition to favorable communication, in particular by tapping inside the small karst shafts exposed on the rock surface.

4.3. The northern portion of ST

ST starts from an older tunnel connecting the bottom of Warren Shaft to the Gihon Spring complex (Fig. 1b). The northern team started hewing ST due west, subsequently swinging toward 290°. At 28 and 33 m (distances are from ST starting point), in the area where ST passes beneath the Dead End Shaft, two corrections in the hewing direction were made by the excavators. As a result, ST swings from 290° to 270°, and after 45 m it turns to 240°. The depth of ST beneath the present topographic surface (bedrock and talus) in the area between Warren and Dead End Shafts increases to ca. 23 m. However, ST passes only about 3 m beneath the bottom of the Dead End Shaft (Fig. 2). This indicates that acoustic communication between the hewers and the surface-control team, using the bottom of the Dead End Shaft, may have played an important role already from the earliest stages of tunnel excavation.

At 73 m, ST is about 50 m beneath the topographic surface – the maximum overburden, noted in the Siloam Inscription as ‘hundred cubits’. Here, where the excavating team was well beyond the range of sound communication, the tunnel swings by 90° from a SW toward the SE direction across a distance of about 7 m. At this point tunnel engineers must have realized that continuous sound communication with the surface is of essence if encounter with the southern team is to be accomplished. Analogous with the workings of the south team, excavation now swung in the direction of shallow overburden, along the eastern slope of the hill. Our argument that corrections were performed during excavation is supported by the analysis of the southern portion (above), where the level was modified during excavation, as dictated by new measurements.

5. ST in the context of tunneling and measurement techniques in the ancient world

The origin of tunneling techniques is linked to ancient mining. This knowledge had been applied for transporting water underground and bringing it to the surface using long tunnels at Urartu and Mesopotamia [24,34]. The ancient Qanat technique, still widely used in Iran, involves excavating a slightly-inclined tunnel branching out from the bottom of a shaft and meeting at about half way with excavators from neighboring shafts. The method was feasible because the small distance between adjacent shafts (tens of meters) reduced the need for precise measurement to a minimum. A similar tunneling method was utilized by Assyrian monarchs (9th–8th centuries BCE) to transport water from distal sources into their cities [9,43,46]. In these systems the tunnels were used mainly to overcome topographic obstacles along aqueduct routes. Another variety of a subterranean water system was developed in Judah and Israel (9th–8th centuries BCE). The latter technique involved construction of a short inclined tunnel from within a fortified city, with the objective of reaching low-lying groundwater sources which were outside the city walls [50,54]. The hydrogeological and engineering expertise gained in these, and other waterworks (e.g. the Middle-Bronze Age systems around the Gihon Spring) must have provided much of the background knowledge for ST engineers.

Significantly, tunneling practice preceding ST incorporated only short segments, which did not necessarily involve precise measurements. The tunneling engineer in charge of the project might have had a crude semblance of a map to suggest where the tunnel had reached at each stage, although we have no written evidence to support this claim.

ST is the oldest accurately-dated long tunnel constructed without using intermediate shafts for the excavation work proper. Although the first stages of ST may have been constructed rapidly, without proper vertical measurements, by the time the final stages were initiated the tunnel design was improved and more careful vertical measurements and horizontal adjustments were made. This is particularly well manifested by the vertical dimension of ST: after the initial apparent vertical mistake, the designers adjusted the southern 86 m of ST by progressive lowering of the tunnel floor. Following the adjustment of the southern 86 m they probably constructed an almost horizontal floor, which could be slightly adjusted after connection was made, in order to reach a continuous gradient. The outstanding precision in leveling is reflected in a vertical offset of only 30 cm at the ceiling level of the meeting point. Such an accomplishment suggests that the surveyors of ST already possessed an instrument similar to the Roman chorobates [56], which is in essence similar to the presently used leveling instrument (minus telescope).

Compared with leveling, horizontal angular measurement is much more complicated, and associated with larger errors. The fact that the constructors shifted ST route to the eastern slope of the city indicates that they did not possess an appropriate horizontal angular measuring method, so they had to rely on acoustic sounding.

The improvement of tunneling techniques allowed the subsequent water systems to be often concealed underground, in long tunnels and pipes [15]. For example, a long tunnel (1040 m) without intermediate shafts was constructed during the early 6th century BCE by Eupalinos on the island of Samos [32]. Comparable to ST, the Eupalinos tunnel was also constructed to bring water from outside city walls into the city proper. The tunnel crossed a mountain ridge taking as short a route as was feasible, with two teams working from both ends. Precise horizontal and vertical measurements were needed here. Later, Hellenistic tunnels maintained the Mesopotamian method, hewing the tunnel outward from a series of shafts [7,16]. Tunneling with intermediate shafts was also practiced by the Romans [40,56].

It may be concluded that ST was an innovative project which advanced the ancient tunneling practice in several ways. Yet, this was initiated in an extremely short time frame of the Assyrian siege which must have stretched the capabilities of the engineers to the utmost limit. The project was probably completed after the siege; if Sennacherib returned to Judah for a second campaign [29], the engineers may have had sufficient time in between the two campaigns to complete the excavation of ST.

Consequently, we do not consider the whole of the strange S-shape of the tunnel as part and parcel of the original design. It is likely that initially the two excavating teams were ordered to start hewing the tunnel along what at that time appeared to be the most convenient route, leaving room for subsequent adjustments to allow acoustic communication between hewers and the surface teams.

6. Conclusion

During most of the 20th century many puzzling aspects of ST have been attributed to natural geological (karst) processes. We have demonstrated that ST must have been engineered and hewn by man without a pre-existing natural conduit, using two lines of evidence: (a) the natural features of ST – the lack of any continuous fissure or remnant of a karst passage, and the natural sediments covering the ancient plaster, and (b) the artificial features – the plaster covering bare bedrock, and the false starts and hewing deviations. We suggest that the word '*zdh*' in the Siloam Inscription refers to the wrong echoes responsible for the hewing deviations close to the central meeting point.

The most probable reason for the circuitous route of the tunnel is that plans and techniques were modified during ST construction. We argue that a water or oil leveling technique was used for the final precise leveling of the tunnel. However, no precise horizontal angle measurement method was apparently available, forcing the excavators to adopt the circuitous route and rely on acoustic communication. Sound contact between the excavators and a surface guiding team, was critical in the execution of the final task just prior to the encounter of the two teams. Acoustic communication was feasible because unlike other ancient ridge-crossing tunnels, the central portion of ST was directed to relatively shallow (8–25 m) overburden. The difficulty of pinpointing the source of the sound could well be the cause of the confusion indicated by the frequent modifications in tunnel directions along the central segment. Notably, acoustic communication is still the classical method used for locating trapped people in mine catastrophes as well as earthquake collapse.

We conclude that ST is a major technological advance in tunneling techniques: (a) for the first time a long tunnel without intermediate shafts was constructed; (b) this was achieved by precise leveling and acoustic communication; (c) the tunnel was plastered in its entirety, clear testimony that the engineers were aware of the physical drawbacks of carving a water tunnel in karst terrain. The radiometric dating of the plaster and covering flowstone, corroborated with the biblical narrative and the Siloam Inscription, pinpoint ST technological advance to about 700 BCE.

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