CHAPTER EIGHTEEN

GREEK ENGINEERING
The case of Eupalinos' tunnel

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1. INTRODUCTION

Greek engineering and technology are generally undervalued, sometimes to the point of being unknown, forgotten, or ignored, in the minds and writing of ancient historians. For example, architecture can be discussed without any reference to how the buildings were constructed; trade can be discussed without any reference to how goods were manufactured; the economy can be discussed without any reference to how silver coins were produced. Our understanding of Greek society is incomplete if we know nothing of the methods by which the Greeks solved significant problems of the ordinary everyday variety, like finding and distributing drinking water, as well as of the rarer kind, like temple building.

To show the sort of interesting Greek achievements which are being overlooked, we shall discuss one outstanding example of Greek engineering: the tunnel of Eupalinos, which was undertaken to bring good water to the population of Samos every day, and was also an extraordinary project.

In Section 2 we briefly describe the island of Samos, and give Herodotus' record of the tunnel. In Sections 3 and 4 we give a full description of the tunnel and discuss its construction in detail. A central technical problem we address is that of the alignment, which is rich in implications for the history of the tunnel and for Greek engineering in general. In Section 5 we discuss some implications of this and other engineering projects for Samian history.

2. SAMOS

Samos is a relatively green and fertile Greek island, about 19 km wide and 45 km long at greatest extent, and about 490 km^2 in area. It is separated from the peninsula of Mykale in Asia Minor by the Samos strait. Archaeological material testifies to the Dark Age in Samos having ended in the ninth century.

Samos was relatively quick to develop. She was one of the first Greek communities to build a monumental temple,[1] to develop ancillary structures in the temple precincts,[2] to explore and settle abroad,[3] to be led by a tyrant,[4] and to build a large and powerful navy.[5] Her historical zenith comes early, in the sixth century.

During this century the fortifications, breakwater and tunnel were built.[6] Slightly

Figure 18.1 Eupalinos' tunnel (southern section looking north).

over 6.4 km in length, the walls enclose the city, the top and southern slope of Mount Kastro,[7] and the farmland between Kastro and the sea. The breakwater extends about 400 m into the sea, protecting the harbour from southerly winds. The tunnel pierces Kastro's west end, and is a little over one kilometre long.

Eupalinos' tunnel was already famous by Herodotus' time. He says, in effect, that the tunnel is the greatest achievement of the Greeks:

> I have talked at some length on the history of the Samians because theirs are the three greatest works of all the Greeks. One is a tunnel[8] through the base of a mountain 150 fathoms high.[9] The length of the tunnel is 7 stades,[10] its height and width are each 8 feet.[11] Throughout its length another cutting[12] 20 cubits[13] deep and 3 feet wide[14] has been dug, through which water flowing through pipes is conveyed to the city from an abundant spring. The architect of this tunnel was the Megarian Eupalinos, son of Naustrophos. This then is one of the three. The second is a breakwater[15] into the sea around the harbour; the length of the breakwater is more than 2 stades, and the sea is 20 fathoms deep. The third of their achievements is the largest of all temples known to us, the first architect of which was Rhoikos, son of Phileus, a local man. Because of these works I have spoken about the Samians at considerable length.
>
> (3.60)

Herodotus gives a full description of the tunnel, as befits its first rank among these three greatest works,[16] and describes the other two works very briefly. It should be noted that by 'works' Herodotus does not just mean engineering works, but works in the broadest sense. Significantly, all the works he specifies are works of engineering. Compare 'the seven wonders of the world', which were also works of engineering.[17]

3. THE GREATEST WORK OF THE GREEKS

The tunnel was rediscovered in 1881 by Abbot Kirillos, and was found to be much as Herodotus described it. It is 1,040 m long;[18] it is a square tunnel, variable in height but generally about 1.8 metres high and wide[19] (see Figure 18.1). It was dug in the sixth century BC through the base of Mt Kastro, a 237 m-high mountain. It was dug to bring water from a spring, now called Agiades, on the north side of Kastro, into the city of Samos, now called Pythagorion, on the south side of the mountain (see Figure 18.2).

The water pipes are laid in a cutting along the east wall of the tunnel. The cutting is 3.38 m deep at the north end of the tunnel, but is sloping, so that at the south end of the tunnel it lies 8.5m below the tunnel floor.[20] For some of its length the 'cut and cover' method of construction was employed. Here the channel was dug out to its entire depth, roofed, and then the cavity refilled with rubble from the roof of the channel to the floor of the tunnel. Elsewhere the cutting was excavated only to part of its depth and the water channel tunnelled through the rock beneath.[21] These two types of working can be seen at the many open 'shafts' between the main tunnel and

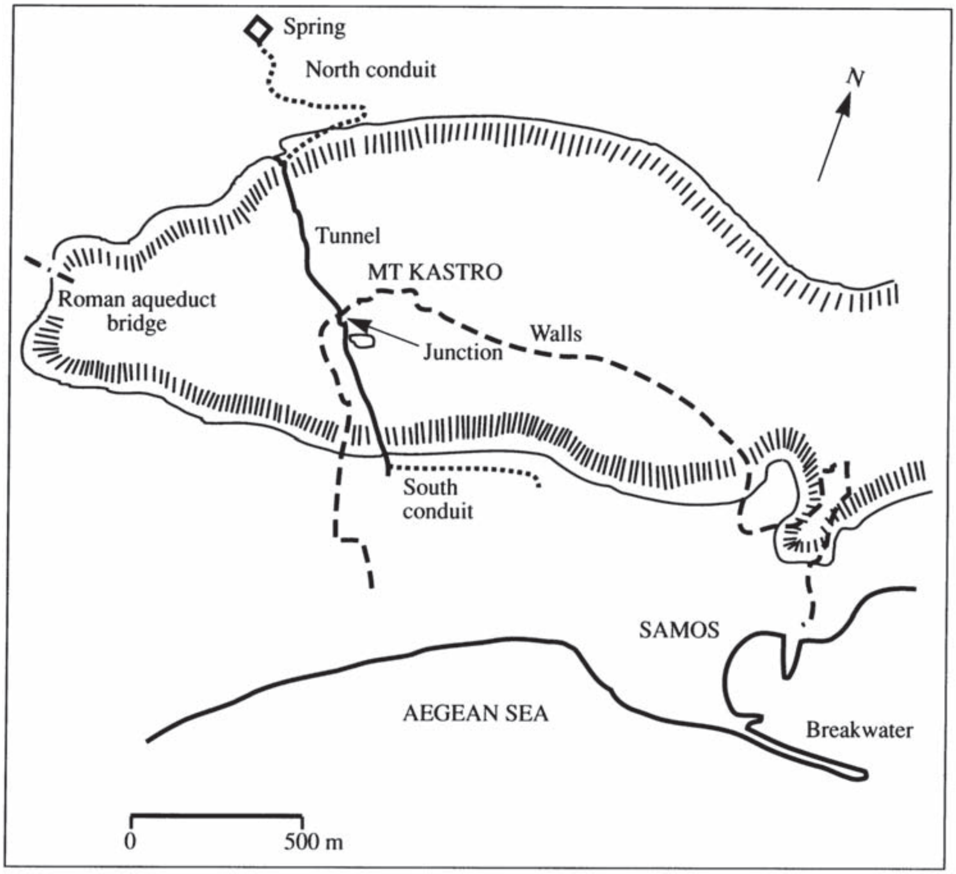

Figure 18.2 The tunnel and environs (after Kienast).

the water tunnel. Some of these 'shafts' are several metres long. At the southern end of the tunnel the water channel does not emerge, so to speak, but carries on through a conduit to the city. There is a separate square entrance to the water channel below and south of the main tunnel entrance.

The one piece of significant information which Herodotus fails to give is that the tunnel was dug from both ends and met in the middle. We know that it was dug from both ends because around its mid-point, the tunnel from the south turns to face *north-east* (towards the *right* from the south-tunnellers' perspective), while the tunnel from the north turns to face *south-east* (towards the *left* from the north-tunnellers' perspective). The tunnel from the north also rises quickly before the junction, and then overshoots the south tunnel at the junction. This would not have occurred if the tunnel had been dug continuously through from one end to the other.

It has been said[22] that had the tunnellers not both deviated towards the east, they would have met head on: they were in perfect alignment. This is not quite true according to the latest survey in Kienast (1990), which asserts that the north tunnel is, at the junction, some 6 m out of alignment to the east. It certainly is not the case that the tunnels are perfectly straight and true along their lengths between their entrances and the points at which they turn to meet. Indeed, it is all the more remarkable that the two tunnels met, given the bends to be found in both before the final bend which leads to the junction.[23]

The steep rise in the original north tunnel floor as it turns towards the junction suggests that the north tunnellers thought they were too low. But by sight it seems that they were on right plane originally, and had they not deviated upwards in the last stretch then they would not have overshot the south tunnel.

The tunnels meet at an angle of about 80°, and upon meeting the faces of both tunnels were abandoned. The floor of the north tunnel was then dug down to a level about 60 cm above the floor of the south tunnel, presumably to ease passage between the two halves[24] (see Figures 18.3 and 18.4).

4. THE PROBLEM OF ALIGNMENT

We do not know by what methods Eupalinos designed his tunnel. Herodotus' reference to Eupalinos and his tunnel is the only specific one which survives in the sources, and Herodotus says nothing on the method of construction.

There are three primary problems which need to be solved by the tunnel-builders:

(1) where to start digging into the mountain-side;
(2) how to find the same level for the north and south tunnels so that they will meet on the same plane; and
(3) how to find the same alignment, so that the two tunnels will meet head on.

4.1 Where to start

Where to start digging at each end will be determined primarily by the purpose of the tunnel. In this case it was to bring water from a spring, on the north of the mountain, inside the city wall, on the south side of the mountain. The water was to flow by gravity, therefore the water channel had to have a slope, but not one too steep, to avoid the water being discharged as a torrent. The water was brought from the spring to the mountainside by a conduit, and since water will not flow uphill, the conduit had to decline between the spring and the tunnel, and the tunnel (where the conduit entered it) had to be a little lower again. So the level of the tunnel was determined at the north end by the level of the conduit, and the level at the south end was determined by the level at the north end.

Given the level, the precise spot at which the diggers began tunnelling into the mountain must have been determined by a number of factors: (i) They would have wanted to make the tunnel as short as possible. Without significantly lengthening the tunnel, at the north end they could have started the tunnel some 100 m before they did, approximately where (because of the terrain) they had to give up the cut-and-cover method previously employed on the conduit, and start tunnelling. However, that would have meant tunnelling under a stream bed—not a good idea when the rock is porous (as limestone is), (ii) They may have had natural ventilation in mind when choosing the location of the tunnel mouth. Exposing the approaches and portals to

Figure 18.3 The junction—the abandoned face of the south tunnel is straight ahead, and the north tunnel joins at left.

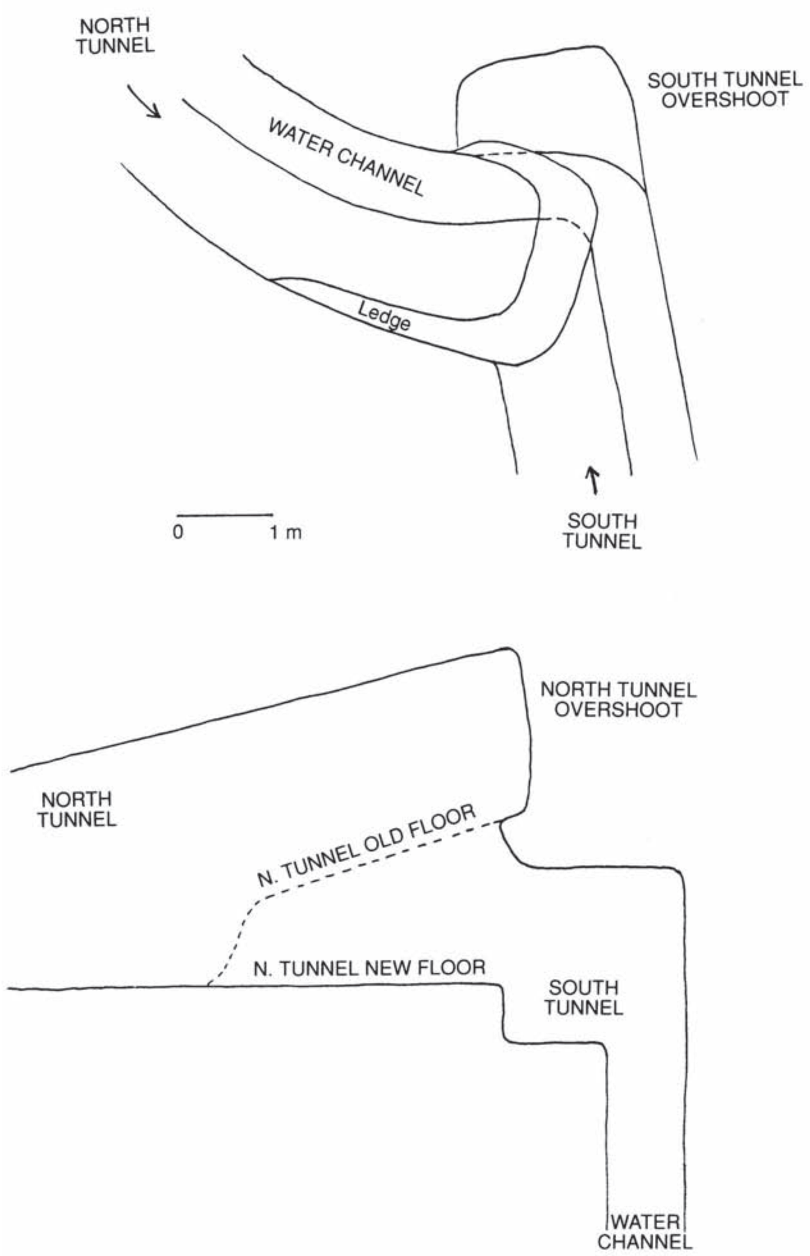

Figure 18.4 The junction in plan (above) and elevation (below).

prevailing winds improves ventilation in the tunnel, and counteracts dampness caused by condensation and water seepage.[25] (iii) Goodfield argued that the spot was chosen because it was 'the only location where it was possible to plant a row of poles as a surveying guide up and over the mountain and keep them in sight all the time'.[26] This was later modified to 'one of the few lines by which one can climb easily and directly up the rugged southern hillside and then down the gentler northern slope to the valley behind'.[27] We cannot agree with this. The route is definitely not 'easy', especially where a long vertical cliff crosses the line.[28] Moreover, many lines over the mountain could probably be found by trial and error. In our opinion, surveying demands had little if anything to do with the location of either of the tunnel mouths.

4.2 Finding the level

Next comes the more difficult question of how to find that level at the south end. Before discussing the possible methods, we should first describe the tools used.

The tools which were used for surveying and sighting are basically three: the groma, the chorobates, and the measuring pole or rod. They were all invented in Egypt before the construction of Eupalinos' tunnel, and were all still in use in Roman times.

The groma is a horizontal cross, mounted on the point of an offset pole, with plumb lines hanging from each of the four end points.[29] It allows one to sight straight lines, and lines at right angles to one another (perpendicular lines).

The second tool is a levelling instrument called the chorobates. It is a bench, preferably about 20 feet long according to Vitruvius (*On Architecture* 8.5.1), with four identical and straight legs attached perpendicularly at each corner, with a crosspiece from the lower part of each leg to some point along the bench. On these crosspieces are drawn vertical lines, and on the bench directly above each line is attached a plumb line. There is also a groove, 5 feet long, down the middle of the bench, which may be filled with water if it is too windy to use the plumb lines properly. The chorobates is level either when the plumb lines hang true in front of the vertical lines on the crosspieces, or when the water is at the rim all around the groove. There were simpler (and smaller) levelling instruments which worked on the same principle, including basic water-levels.

The third tool, the measuring pole or rod, is basically a very large ruler, about 10 cubits long according to Hero (*Dioptra* 5), with a plumb line and a vertical line drawn somewhere on it (to ensure that the rod is vertical when in use), a black and white sighting disk, and a more or less sophisticated mechanism for reading off the measurement.

These then are the tools of the trade, whichever method was used to design Eupalinos' tunnel.

There seem to be two possibilities for finding the same level at the south end as at the north end.

4.2.1 The poles-over-the-top method

One method is by the use of measuring poles over the mountain, and a lot of very basic arithmetic (i.e. additions) to measure the height up one side of the mountain and down the other. Starting at the north end where they wanted to dig the tunnel mouth, the surveyors stuck a measuring pole in the ground. Then they set off up the mountain, preferably (but not necessarily) in a straight line, and preferably (but not necessarily) along the straight line they wanted the tunnel to go, sticking in measuring poles as often as was needed to ensure that they could sight horizontally from the top part of one pole to the bottom part of another. When they got to the top, they stuck a pole in at the highest point. They added up all the height readings taken from pole to pole up the north side, and got a figure *h,* which was the height from the tunnel mouth to the top of the mountain. They then repeated the process coming down the other side, reading off the measurements and adding them together until they got to the same figure *h*. That was the same level as the north end of the tunnel, and was the level at which the south entrance should be dug to give a horizontal tunnel.

Given the slope of the mountain and cliffs along the route of the tunnel, in our opinion scaffolding would have been necessary if the poles followed the projected line of the tunnel. Scaffolding would have been readily available nearby if the tunnel was being constructed at the same time as the fortifications, which enclose the top of the west end of the mountain and run down to the sea, on the south, crossing the line of the south tunnel (recall Figure 18.2). However, this method to find the level does not demand that the poles follow the line of the tunnel; all one needs to know is the height up and down the mountain, and a zig-zag approach is as good as (and a lot easier than) a direct line.

4.2.2 The poles-round-the-mountain method

The other method of finding the level at the south end is to go round the mountain from the north end, preferably (but not necessarily) on the level. As with the poles-over-the-top method, the difficult way would be to try to walk around the western end of the mountain on the contour-line of the north entrance; the easy way would be to go down to the stream bed to the west nearby, measuring the drop as one went down, and then measure up the hill on the other side. The relatively difficult contour-level route would again almost certainly require scaffolding; the easy route would not.[30] Of course the topography may have changed considerably over 2,500 years. Erosion has certainly occurred; the first couple of streets in from the harbour of Pythagorion are sitting on the silted up part of the harbour of Samos[31]—silt which presumably was soil on the south eastern slopes of Mt Kastro in Eupalinos' time.

4.3 Finding the alignment

The problem of alignment is, first, how to know in which direction to start digging, and second, how to know in which direction to dig once one is inside the mountain.[32] Finding the alignment inside the mountain is an important practical consideration, since the entrances at both ends of the tunnel are *not* on the tunnel alignment, but veer west of it.

4.3.1 Over or around the mountain

If the poles-over-the-top method was used for finding the level, *and* if the poles were set on a straight line *and* on the projected line of the tunnel, then the alignment over the mountain would already have been evident, and the problem would have been to know that alignment once the tunnellers were inside the mountain and unable to see the line of poles pointing the direction. If this particular method was used to find the level, one cannot help wondering why they did not dig into the hillside on that line, but at both ends moved several paces west and dug in at an angle such as to meet up with that line some 7 m inside the hill (at the north end) and 15m inside the hill (at the south end).

If the poles-round-the-mountain method was used to find the level, then how could the tunnellers know in which direction to dig at the start of the tunnels, as well as once they were inside the mountain? There is a solution to the first of these problems in Hero's *Dioptra*. This treatise describes the construction and use of a sophisticated sighting instrument Hero invented. One of the examples he gives to show how the dioptra would improve performance in surveying concerns the problem of digging a tunnel from both ends (chapter 15).[33] Note that the method employed in this example could be followed with any sighting equipment: it does not presuppose use of the dioptra.[34]

With reference to Figure 18.5, the method described by Hero works as follows. Given a mountain ABCD and located points A and B for the tunnel mouth on both sides, sight around the mountain from one point to the other by a series of perpendicular lines, say AE, EF, FG, GH, HI, IJ, and JB in Figure 18.5. A right-angled triangle can be projected through the mountain, with its hypotenuse marking the line of the tunnel. The length of the other two sides AK and KB of the triangle can be

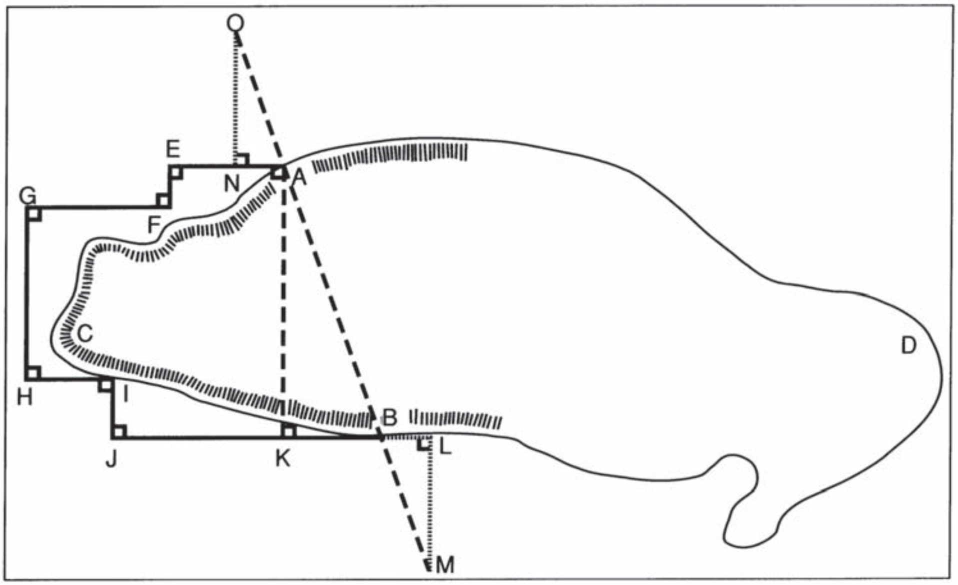

Figure 18.5 Hero's method for finding the alignment.

calculated from the length of the sighting lines round the mountain, and their ratios found:

AK=EF+GH+IJ.
KB=(HI+JB)-(AE+FG).

Now that we have the ratios of the sides of the triangle, smaller similar triangles (i.e. triangles with identical angles) AON and BML can be constructed at the points of entry, and their hypotenuses will show the projected line of the tunnel, and thus show the direction in which to dig. If this method was used by Eupalinos, then neither of the distances AK and KB, which must be determined by addition and subtraction, should be more than 1000 m.[35]

There has been some debate over which method Eupalinos used. In 1903 Schmidt suggested Hero's method had been used; van der Waerden (1954), Burns (1971) and others have followed this suggestion. Kastenbein (1960) suggested that the easiest method would be use of poles and a survey to find the base level, without making any mention of Hero's method. Kastenbein may not then have known of Hero's method. Six years later he wrote again on the subject, and said that Hero's method was feasible and that it was impossible to decide which had been used (1966).

Meanwhile Goodfield (1964) had denied that Hero's method was used, and suggested that all that was required was the poles-over-the-top-in-a-straight-line method. Kienast (1990) does not mention Hero's method, assuming that a very detailed survey was undertaken, and that the poles-over-the-top-in-a-straight-line method was employed. Further, he adapts the poles-over-the-top method to give an account of the angular deviation in the north tunnel.[36] He does not mention that both entrances are off the alignment of the tunnel, nor explain how this misalignment—which is inconvenient for his proposed method[37]—was overcome.

Neither method solves the problem of finding and holding the alignment once inside the mountain. If the entrances were aligned and if the tunnel was straight this would be less of a problem, but the entrances are not aligned and the tunnel is not straight: there are some serious wiggles through the tunnel's course in both sections, but particularly in the north.

The non-aligned entrances are problematic, and have not to date received the attention they deserve: we give here our own observations on them.

4.3.2 The entrances

Both south and north entrances to the tunnel descend steeply, starting from a point slightly west of the tunnel alignment (see Figures 18.6 and 18.7). The south portal staircase is 58 cm wide and 2.28 m long, with a 3.25 m drop. The bottom of the staircase leads to a long built section (called an adit) of dog-leg shape, which has a strongly gabled roof. The first leg (6 m long) has a slight decline, and the second leg (7 m long) has a slight incline, which brings it back up to the tunnel level. The third and last section of the south entrance (6.4 m long), which is perfectly on the tunnel alignment, has a 80 cm^2 square, stone-lined vertical shaft about mid-point. The shaft was constructed and dressed carefully. See Figure 18.6.

Beneath this adit, the south conduit continues south on the line of the tunnel. Its

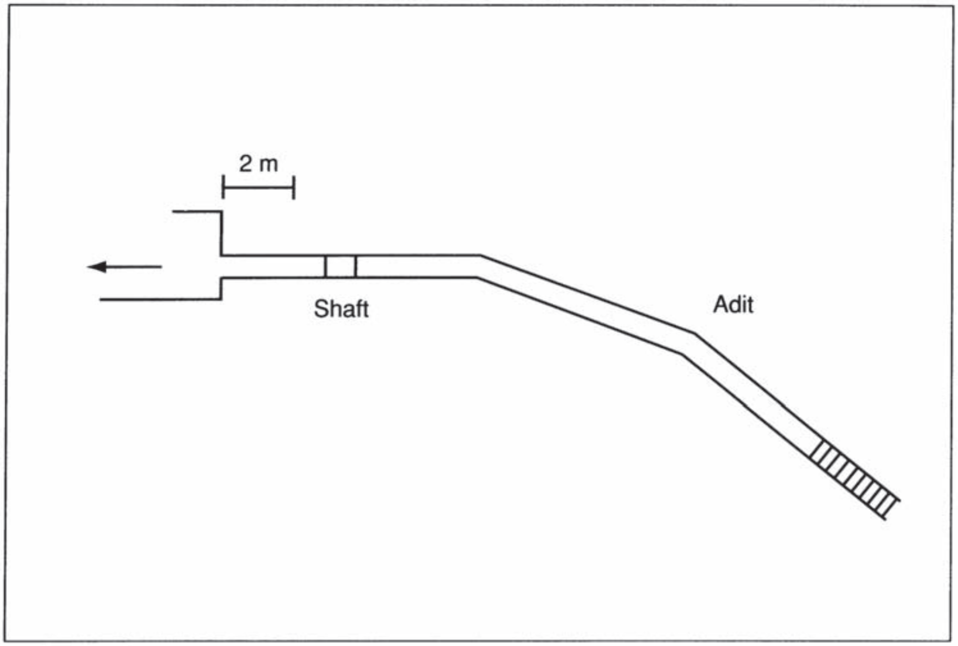

Figure 18.6 South entrance.

own access entrance (the second lower entrance at the south end) is also on the line of the tunnel, about 25 m to the south of the main entrance.

The portal at the north end lies rather more sharply west of the line of the tunnel, and is much more simple in design. The slightly curving staircase, which is 1.15 m wide narrowing to 58 cm at the bottom, and 7.1 m long, descends to the correct level. The bottom of the north staircase opens directly onto the tunnel proper, which is lined on the left, only 90 cm wide in this part, and goes off to the right at an angle of approximately 30°. See Figure 18.7.

The north conduit enters the east wall of the north tunnel 9.5 m from the bottom of the staircase. It enters from the east at an angle of approximately 80°, in a rectangular recess about 1.2 m deep and 3.3 m wide. There is a huge drop (about 9 m) between the ceiling and the floor of the conduit in this section, adjoining the tunnel. The (later) lined section starts 3 m further in.[38]

We assume that Eupalinos' tunnellers knew where they wanted to go into the mountain; at what precise spot (in three dimensions) they would need to start digging at both ends. Digging horizontally into a sloping hillside may have risked roof collapse at the mouth of the tunnel, since the ceiling was unsupported, or slope slide,[39] since there appears to have been no portal headwall to retain the earth behind. Either in the planning or by trial and error, Eupalinos or the tunnellers would have realized that the entrance should (ideally) be dug at about a 90° angle to the hillside, so that the roof had as much support from the surrounding rock as was possible, and the surrounding rock and earth were disturbed as little as possible. Both entrances

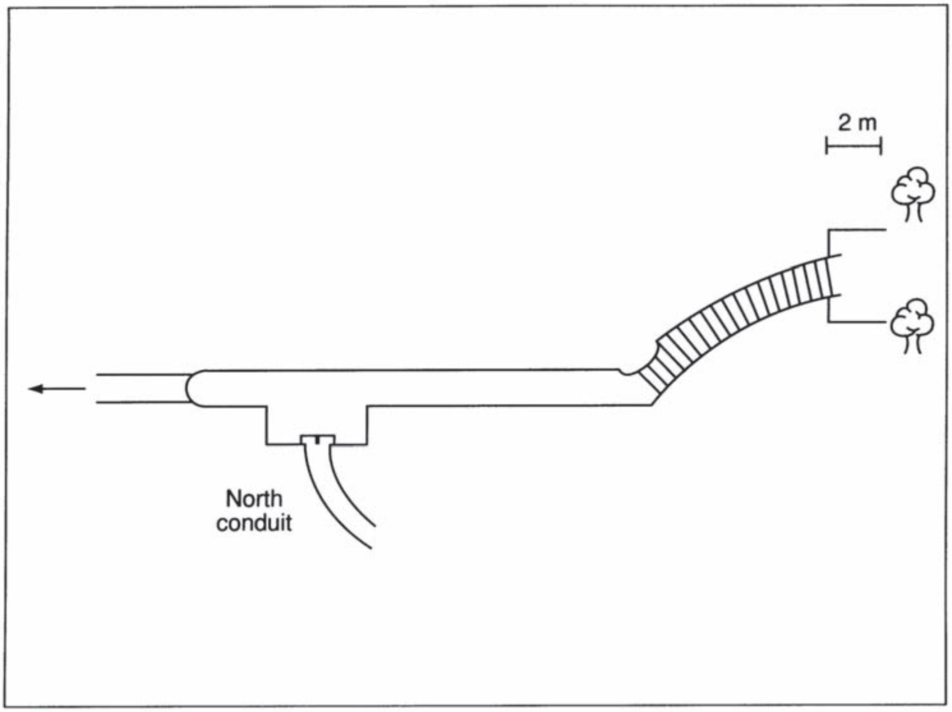

Figure 18.7 North entrance.

have a sharp incline (about 55° from the horizontal at the south entrance), with steep steps down. Both are relatively narrow and lined by stone walls.

However the tunnellers found the correct alignment once inside the mountain, they set off and dug through the mountain holding their line and their level remarkably well in the circumstances.

4.3.3 The junction[40]

In due course they approached each other. Both gangs turned about 40° towards the east—the north crew turned first west,[41] then swung round east, producing a scythe-shaped bend. They seem to have realized that they could easily pass each other in the rock if they were running parallel instead of head-on; if they both turned toward the same direction, so long as they were in the same horizontal plane, sooner or later they were guaranteed to cross paths, and meet. The north tunnellers, besides originally turning west rather than east, also started heading upwards; they seem to have thought (mistakenly as it turns out) that they were too low. To give some idea of the sort of time and distance involved here, given an estimated 5–10 years to dig the tunnel and a uniform rate of progress, they were still some way apart when they began the final, and crucial, section: it could have taken about 3 to 6 months to dig from the points where they each start their final bend to the meeting point.[42]

Clearly, they thought they knew where they were relative to the tunnel projection:

they knew how long the whole tunnel was supposed to be, and how far each team had dug. To know the total planned length, they must have been able to measure or calculate it from the distance over or around the mountain. To know how far each team had dug they could, of course, measure from entrance to face.

4.3.4 Measurement and computation

What measurements and calculations were involved in digging the tunnel, and how were they performed? What geometrical knowledge was needed or available on Samos in the sixth century BC?

Finding and holding the alignment is more complicated than finding and holding the level, especially if Hero's method was used. In the additions and subtractions of measurements, the numbers were not small (although this depends upon the units chosen). Distances of the order of 1,000 metres are not excessively large in units of stades, plethra, fathoms, cubits or feet, and we must assume that manipulation of such numbers was within their capabilities.

The estimation of the length of the tunnel was an essential calculation. If the alignment was established using the poles-over-the-top-in-a-straight-line method, then the length of the tunnel could be computed by adding together the horizontal distances between the poles.

If it was performed using the data obtained from Hero's method then the calculation would increase in complexity. To Hero in the first century AD, the length AB (see Figure 18.5) was easy to determine using Pythagoras' theorem (proposition 47 in Euclid *Elements* Book I): $AB^2=(AK)^2+(KB)^2$. This calculation increases the size of the numbers, and the solution involves square roots (for which good approximation methods were known to Hero). To illustrate Hero's method applied to Eupalinos' tunnel, suppose AK=950 m, and KB=360 m, then AB=1016 m. However, we need not assume that Pythagoras' theorem was used to compute the length of the tunnel. To calculate AB it is possible to transform ABK to a smaller triangle A'B'K', whose two sides containing the right angle are say $1/100^{th}$ of the corresponding sides of ABK, and obtain A'B' from measuring an exact drawing of A'B'K', from which AB=100×A'B'. This geometric rule of thumb falls short of Pythagoras' theorem (but it is an easy corollary of it).

There must have been considerable geometrical activity in sixth-century Samos,[43] required by the immense building projects. Few traces of this activity and the people involved can be found in literary sources. However, Theodoros, a younger contemporary of Rhoikos, is credited with the invention of the carpenter's square.[44] The simplest carpenter's square is a small wooden right-angled triangle, in which the piece forming the hypotenuse is attached to the other two sides at equal distances from the corner. Pythagoras was born into and grew up within this environment, though his dates, like those of Rhoikos and Theodoros, are uncertain. We conjecture that the building projects had greater influence on Pythagoras than Pythagoras had on the building works. Eupalinos did not need mathematical training by Pythagoras (or anyone else on Samos); he was the expert brought in from Megara to construct the tunnel.

To establish the geometrical basis of Greek engineering is an important task. We believe that it may reveal that the origins of Greek mathematics lie in Greek engineering (rather than in the trance-like contemplation of truth and beauty).[45]

4.3.5 The north tunnel

At the junction the cut down floor of the north tunnel is 58 cm higher than the floor of the south tunnel. The north tunnel seems to have a slight incline through the scythe-shaped bend, perhaps caused by the levelling operation after the two tunnels had met. If we understand Kienast (1990) correctly, in the central section of the north tunnel,[46] after an approximately 30 m straight line section, the tunnel veers to the west, and then to the east, coming back on alignment about 200 m from the north entrance.

From the north entrance, for most of the first two hundred metres, the tunnel is quite claustrophobic (see Figure 18.8), being narrow (only 62 cm wide at most points), lined, gabled, low (less than 1.6 m to the top of the gable), the floor irregularly punctuated by a shaft to the water channel running directly beneath, and consists of a series of straight sections at slight angles to one another, of the kind found in the south adit. It is, however, reasonably level. After about 185 m the tunnel opens out, no longer being narrowed by lining, the water channel reverts to the east wall, and the floor begins to rise gently. According to Kienast the tunnellers were forced to rise to try to overcome water seeping into the tunnel about 200 m in from the north end. It seems that the tunnel was intended to be horizontal. Also according to Kienast the first section of the north tunnel is straight and is on alignment, which may be true in theory and in the survey results (allowing the lined passage to roam over the full normal width of the tunnel, rather than following the central line), but runs contrary to the experience of being in this section of the tunnel, where it is impossible to see beyond one straight stretch at a time because of the angles between each stretch and the narrowness of the passage.

4.3.6 The time scale

The tools for digging were a hammer, chisel, lamp, and (probably leather) bucket. How effective were they? What rate of progress did the tunnellers achieve? We can estimate this as follows. The meeting point is not in the middle of the tunnel, but is 620 m from the north entrance and 420 m from the south. Suppose that both teams of tunnellers dug simultaneously, at an equal rate of progress, and that work went on every day of the year.[47] Further suppose that the digging ended when they met, so that the time it took to build the tunnel was the time it took to build the longest 'half' (i.e. the north tunnel).

If we assume that the tunnel took 5 years to complete,[48] then the dig rate would have been 34 cm per day.[49] If it took ten years to complete, then the progress rate would have been 17 cm per day.[50] At the same rates of digging, the south (shorter) tunnel would have taken 3.4 or 6.7 years respectively. Thus the north tunnel could have been started approximately 1.6 years[51] or 3.3 years[52] before the south, and would have progressed about 200 m[53] before the south tunnel was begun. We suggest that this is what happened: that the tunnel was started in the north quite

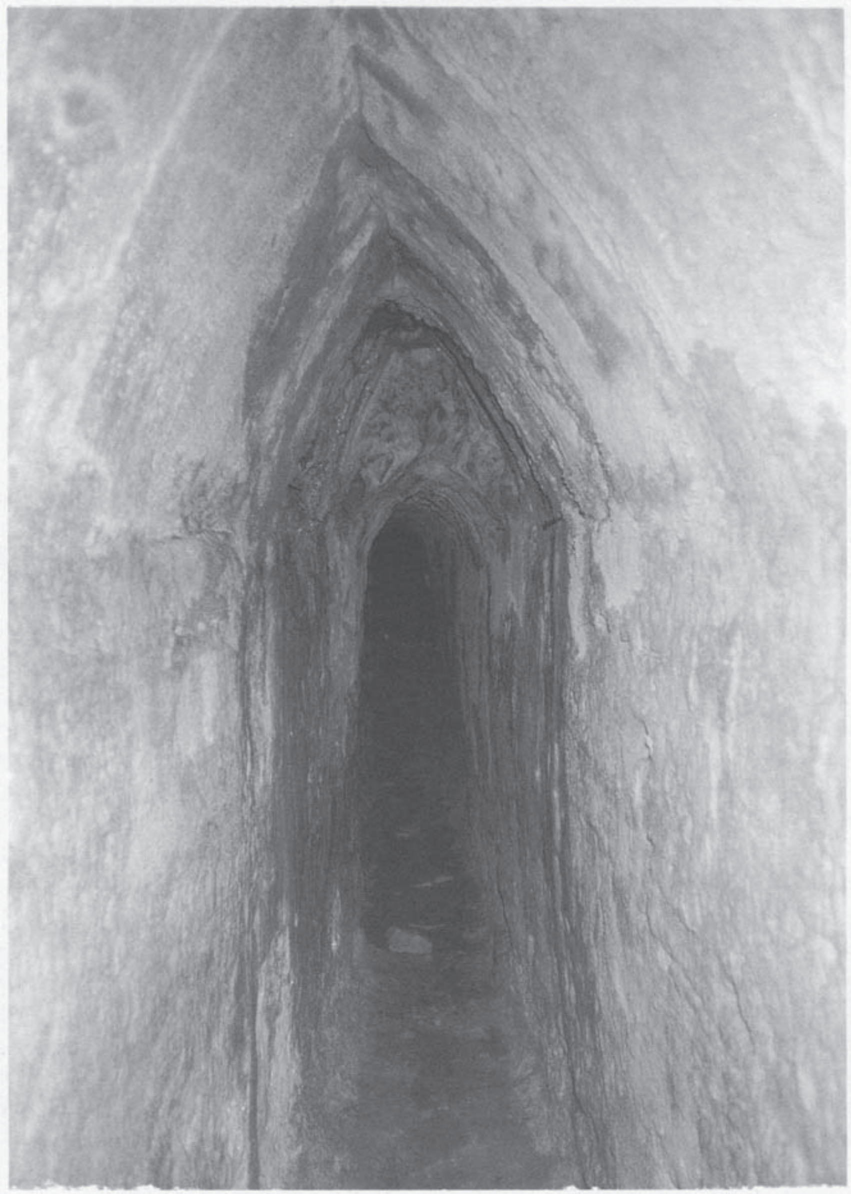

Figure 18.8 The north tunnel (lined section).

some time before work began at the south end. We suggest further that the tunnel was originally planned to be dug straight through in one direction, from north to south. Under the assumption that Eupalinos knew the length of his projected tunnel, he could estimate the time it would take to complete. If the tunnellers were digging at the nominal rates given above, at an early stage in the digging of the north tunnel Eupalinos could estimate the time of arrival at the south end. For example, suppose that they reviewed their position after one year. At the faster rate they could have dug 124 m;[54] at the slower rate, 62 m. That would give an estimated time of arrival at the south end in a further 7.5, or 15.5, years respectively.[55] These calculations are speculative, because we do not know the digging rate; but Eupalinos *did* know it, and he could have calculated an estimated completion date.

4.3.7 The shaft

The shaft connecting the tunnel to the surface at the south end is a unique feature in the tunnel (though such shafts are seen over the conduits at both ends). Goodfield suggested that alignment within the tunnel was achieved by using the light coming in from the shaft behind as a leading light: if it was straight behind, the tunnellers were on target. There is a problem with this reasonable idea for holding the alignment: it fails to explain how the north tunnellers held their alignment, for there is no shaft at the north end.[56] However, if there was not originally any plan to meet up with a tunnel coming from the south, there was no tremendous pressure on the (north, and in the beginning the only) tunnellers to hold very precisely to a certain line. If, as we suppose, the south tunnel was planned and started later, only *then* did it become essential that both tunnels stuck to a planned course. The north tunnel was already well on its way—about 200 m is a reasonable estimate (see above 4.3.6). The south tunnel was not yet begun. Tough engineering demands (finding and holding the level as well as finding and holding the alignment) were placed on the south tunnel, from the first strike of the chisel to the last. The same demands were placed on the north tunnel from this point.[57] The exact position (in three dimensions) of the north tunnel face had to be established, and any changes in current alignment required to meet up with the south tunnel calculated.

Meanwhile, at the south end, the shaft was dug exactly on the line of the tunnel, and to the required depth. The shaft was carefully lined with stone, square with the line of the tunnel. The section of the tunnel either side of the shaft for about 3 m was also lined with dressed stone. By ensuring that the shaft was square and on line, and that the built section fore and aft was square with the shaft, did they use the light from the shaft and the 'mini tunnel' of the built section to dig straight ahead by looking behind? By lining the tunnel around the shaft, they narrowed its width, and thus the beam of light from the shaft was more central and sharp. The gable roof emphasizes both (see Figure 18.9).

We suggest that the south end only has a shaft because it was started later; the original plan was to dig through from the north. The south end had to follow the alignment from the word 'go!'.

4.3.8 The water channel

The tunnel's function was to transport water. To transport water by gravity, a sloping tunnel was required. This was the purpose of the water channel/tunnel dug along the east wall of the tunnel. This double tunnel construction is found in other underground conduit systems, for example those of Syracuse, Akragas and Athens.[58] This method of construction was probably employed because it was extremely difficult with the tools of the time to hold a constant shallow slope, whereas there were adequate tools to hold the horizontal. The most important part of the job in Samos was ensuring that the tunnels met under Kastro; once connected, the required sloping channel could be cut by incremental increases in the depth over certain units of distance, or by sinking shafts of increasing depth and connecting them by trial and error. The actual gradient is 0.5 per cent. The lower channel would also serve as a drain for water seeping into the tunnel.

Figure 18.9 The shaft.

5. THE SOCIAL CONTEXT

5.1 Introduction

Samos must have looked like a building site for a large part of the sixth century BC. Quite apart from any civil or domestic building going on in the city, the breakwater was being built about 400 m out into the sea; city walls, about 6.4 km long, 6 m high, and 2 m wide, were being constructed with carefully dressed stones (some of them huge; see Figure 18.10); 31 towers were being constructed, even more carefully and to greater height, along its length (see Figure 18.11); a moat was being dug[59] immediately outside the city wall on the coastal plain to the west of the city; the tunnel was being dug through the mountain; and the south conduit was being tunnelled through from the south entrance of the tunnel to the distribution point in the north-west quarter of the city. Round the far side of Kastro, the spring was being contained in a covered, waterproofed reservoir, and the north conduit cut and covered from the reservoir to the north tunnel. And further west along the coastal plain, at the Heraion, 'the largest known temple in the world' was being constructed. Cranes, hoists, scaffolding, wagons carrying building stone and excavated material, and above all, men at work on these projects, would have been conspicuous to all who lived or worked in Samos at the time. One should try to imagine the buzz of activity on these spectacular projects, and the atmosphere which it would have created.

The question of means and motives must be asked of any building operation. How and why were the Samians able and willing to undertake these outstanding projects?

5.2 Resources

Resources required for these projects are of two main types: labour and materials. Skilled labour—highly skilled labour—was required for the planning, surveying, and supervision of the water system, fortifications, and breakwater. It is necessary to emphasize that skilled does not mean infallible. There is a tendency in historical study to assume that everything done was intended to be exactly as it turned out to be. That assumption is contrary to experience, and is occasionally proved to be false. To cite a proven case of an error in tunnelling, Nonius Datus (C2 AD) was responsible for the construction near Saldae (Numidia) of a tunnel half the length of the one in Samos. He later erected a stone pillar, about 2 m high and 50 cm square, to explain to the world why the two halves of his tunnel had failed to meet and needed remedial action: it was, he insists, not *his* fault, but the tunnellers', who had not followed his drawings. Both gangs had veered to their right, and in consequence they had passed each other in the rock.

In the case of the Samian water system we know, thanks to Herodotus, that the islanders bought in the requisite expertise in the person of Eupalinos, who came from Megara.[60] We do not know who had overall responsibility for the fortifications and breakwater. The Heraion was designed and supervised by two local men, Rhoikos and Theodoros.

Tunnellers hewed rock in a confined space, in almost total blackness, in poor air, and in considerable danger.[61] Plasterers made waterproof cement and sealed the

Figure 18.10 Samos fortifications.

Figure 18.11 One of the towers. The breakwater can be seen to the right.

reservoir.[62] Stoneworkers quarried, cut, and fitted the stones for walls, towers, breakwater, tunnel entrances, and lining of part of the north tunnel where roof falls were threatening or had occurred. Joiners made and repaired scaffolding, cranes, and heavy wagons. Crane-men hoisted and lowered stones into position. Timber-merchants acquired and supplied timber of various woods and sizes as needed. Rope-makers made and repaired heavy ropes. Potters made thousands of interlocking water pipes. Labourers assisted by fetching, carrying, and holding materials as required.

The Samians could not have recruited all these people, especially the skilled and semi-skilled specialists, from among their own ranks. Normal levels of activity could support only a very small number of specialist craftsmen in a given community.[63] A major building project posed skilled labour demands which outstripped local supply, even in the case of one moderately sized temple.[64] We can only guess the numbers of men and proportion of foreign craftsmen involved in these projects on Samos, but estimates of numbers and diversity should be related to the supposed speed and synchronism of the works.

There may have been Lakonian craftsmen involved on the projects. There is literary and archaeological evidence to suggest that some form of 'special relationship' existed between Samos and Sparta from the late seventh century, if not before.[65] In particular, a high proportion of all Lakonian decorated vases made between 580 and 550 found outside Lakonia are found on Samos, which finds *may* be the fruits of plundering activities, but the same cannot be said of a bronze lion which was dedicated to Hera at the Samian Heraion by one Eumnastos the Spartiate, *c.* 550. This 'special relationship' might have encouraged Lakonian craftsmen to work on Samos, especially if the relationship was based not just on ties of *xenia* between individuals and mutual rendering of military services in the past, but there existed *symbolai,* or interstate agreements, which gave members of one state some protection when in the other.[66]

If we turn from men to materials, the one-kilometre tunnel required approximately 3,370 m^3 of excavated material to be removed and dumped elsewhere (this figure excludes the water channel and conduits). This is *minute* in comparison with the quantity of stone and rock required for building about 6.4 kilometres of walls and 31 towers. About 2.5 km of clay water pipe had to be made. Inestimable quantities and variable qualities of timber, glue, rope, lime, and plaster were consumed in the construction work. We do not know how much money was required to pay the workmen, or even that they were paid.[67] Costing out such a project is difficult because of the lack of information in the sources. At Epidauros in the fourth century, excavation costs for channels for the water supply varied from 1 dr. 1 obol to 2 dr. 3 obols per foot.[68] Such figures, even when given for stated units of measure rather than for the whole contract, do not help us cost even the water channel within the tunnel. We do not know, for example, whether variations in price reflect difficulties experienced in different sections, or different times taken to complete the work, or something else. Even if we knew in detail the relevant costings for the temple-works at Epidauros, we could not apply them to Eupalinos' tunnel, because excavating topsoil and bedrock in the open is altogether different from excavating unweathered rock in a tunnel.

The resources consumed by these projects in Samos were vast, by any standards. Even allowing for the use of slave labour, local stone, local earths, local timber, local hemp, and so on, these projects represent a huge cost in terms of time and effort to acquire and exploit labour and materials, to say nothing of opportunity costs (i.e. the value of alternative work which the labour force might otherwise have done, and alternative use of the materials consumed).

5.3 Motives[69]

The fortifications were not built in a hurry. The high standard of building and finishing of the stone suggests that their construction was precautionary, rather than as a reaction to some concrete and more or less immediate threat. Samos was acquiring plenty of enemies through her piracy and plundering. It is indicative that Herodotus' entire excursus on Samos (3.39–60) concerns or revolves around Samian plundering activities.[70] The name of the first tyrant of Samos, Syloson, means 'booty-securing'. Its choice as a name or nickname suggests a certain level of achievement in this field, either by himself or his father, and a readiness to boast about it publicly. A co-operative of privateers, in Miller's phrase,[71] graduated into a very powerful fleet under orders. Also, from the middle of the sixth century, there was the growing (but usually distant) threat of a major power attacking—Lydia, Persia, or even Egypt.

The planning of the tunnel presupposes the planning of the walls. The spring is outside the walls, so something had to be done to bring its water inside the walls in case the city was besieged. The tunnel does not appear to have been dug in a hurry. The sides, top, and floor of the tunnel are cut neatly and squarely. Why did they tunnel through the mountain rather than run a conduit around it? The north conduit is long anyway (890 m), so arguments about security are weak: enemies only need to find one shaft to cut off or poison the water. Compare Roman aqueducts: most aqueducts were built underground for 90 per cent of their length,[72] but the Romans also built sections on arches, which were (very obvious) vulnerable points. The argument about security is further weakened by the fact that elsewhere in Greece systems constructed entirely within the walls of a city are constructed in the same manner to the same standards.[73]

The answer to the question 'why did they go through the mountain rather than round it?' lies perhaps in the fact that tunnelling is tunnelling, whether one is digging 3 or 300 m below ground. If not using the shaft method of construction, it makes little difference in practice how deep the tunnel is (given the parameters of tunnel construction in antiquity). The topography at the west end of Mount Kastro made the cut-and-cover method employed for the first 700 m of the conduit unworkable, forcing the diggers to tunnel thereafter. And if one is tunnelling, the shortest route is preferable.

Why then did they dig such a large tunnel for the alleged purpose? The answer to this is perhaps that its internal dimensions would allow work on the 'real' job of digging the water channel to proceed more easily.

Why did they dig from both ends when they could have dug from one end? The obvious answer to this question is to complete the job more quickly. Working from both ends allows the job to be done in less time, since twice as many people can work on the tunnel at the same time. The dimensions of the tunnel suggest that four men could have been employed on each face at any time: two on the heading (the top half of the tunnel), digging in advance of two more on the bench (the bottom half). We have suggested above (p. 418) that the south tunnel was started later than the north tunnel because completion was desired or needed earlier than the estimated time of arrival of the tunnel from the north end—perhaps because the walls were nearing completion, or because an external threat was anticipated or appearing.

The breakwater gave protection to the harbour, and the ships within it, from the prevailing southerly winds. By the last quarter of the sixth century the Samian navy was one of the most powerful navies, if not *the* most powerful Greek navy, in the Aegean. Comprising about 100 pentekonters, plus triremes and 'Samians' (which design combined some of the features of a merchantman with a warship), and having a crucial role to play in the Samians' generation of income and influence as well as in their defence, the fleet needed a safe port.

5.4 The place of engineering in society

Thanks to the success of later Greek science and philosophy, and the prejudice of some ancient and many modern commentators, we are led to believe that the Greeks valued pure science and disdained applied science; that the Greek intellectual lived in a chryselephantine tower, pondering pure idealized forms, and shunning, if not actually snubbing, the real world and the real people who dwelt in it. As we have seen, Herodotus did not share this view. Apart from Eupalinos, see also (for example) his story of the sixth-century Samian engineer Mandrokles, who bridged the Bosphorus for Darius (4.85–9). Likewise, Thucydides records (for example) the Corinthians' contribution to ship design and the name of Ameinokles, the Corinthian shipwright who designed the 'Samian' ship (1.13).

Many centuries later in the Hellenistic period (the 'golden age' of Greek science) Arkhimedes became famous in his lifetime for his marvellous physical discoveries and mechanical inventions:[74] the bath story, which concerned the real-world problem of a fraudulent goldsmith; the water screw, which concerned the real-world problem of water lifting; and the anti-siege devices, which concerned the real-world problem of Roman soldiers at the gates of the city.

However, Plutarch, writing many more centuries later, asks us (in a much quoted passage) to believe that 'although [Arkhimedes'] inventions had earned him a reputation for almost superhuman intellectual power, he would not deign to leave behind him any writings on his mechanical discoveries. He regarded the business of engineering, and indeed of every art which ministers to the material needs of life, as an ignoble and sordid activity, and he concentrated his ambition exclusively upon those speculations whose beauty and subtlety are untainted by the claims of necessity.'[75] That records Plutarch's view of engineering, not Arkhimedes'. Plutarch is also wrong: Arkhimedes 'deigned' to write a work *On sphere-making* (which is lost), and *The Method* (which was rediscovered in 1906). Arkhimedes developed some of his mathematics using a mechanical method, based on the lever principle, by which he could discover mathematical results, which he then set about proving.[76] Moreover, it is highly significant that Arkhimedes wrote about his method. As Sarton pointed out, few scientists explain their method of discovery, because the first intuition may be vague, difficult to express in scientific terms, perhaps unsubstantiated by theory, and certainly difficult and tedious so to substantiate.[77]

Geometry was not an élitist game, known only to the wealthy and educated few and practised by them for sport. It was used by engineers, architects, shipbuilders, housebuilders, and numerous other people. Vitruvius argues that Pythagoras of Samos, Aristotle of Stageira, Plato of Athens, Arkhimedes of Syracuse, Arkhytas of Taras, Eratosthenes of Cyrene, and Demokritos (of Kroton?) deserve honours at least as great as those awarded to athletes because their researches 'are an everlasting possession, not only for the improvement of character but also for general *utility*' (our italics). Moreover, athletes cannot '*do for human life* what is done by the researches of the learned'.[78]

Similar sentiments are expressed by Plutarch's contemporary Pliny the Elder, who, after discussing sculpture, painting, polished marble structures, obelisks (Egyptian and Roman), the pyramids, the Sphinx, Pharos lighthouse, labyrinths, temples, sewers, palaces, and theatres, says 'Let us now move on to achievements which are unsurpassed *because of their real value*', by which he introduces the subject of aqueducts and water supply.[79]

6. CONCLUSION

Confronted by the tunnel, the primary question is: how was it constructed? As we have seen, this leads to many separate technical questions, some of which have no answer at the present time. The analysis of the tunnel is heavily dependent on the comprehensiveness and accuracy of surveys and their publication.

We have tried to show how study of engineering projects such as that of Eupalinos' tunnel influences and can improve our understanding of Greek history (most obviously political, social, and economic issues). It gives insights into the needs, ambitions and abilities of the society which commissioned, built, and used the engineered object or system. Much remains to be discovered, clarified, and confirmed to enrich the picture of the world of Eupalinos of Megara and the tunnel he built on Samos. The same is true of all parts of the Greek world. Behind every good temple is a good engineer. At present, engineering is the barely excavated foundation for the glory that was Greece.

NOTES

1 The hekatompedon, built soon after 800. The Rhoikos temple, the first of the great Ionian temples, was built *c.* 570–60.
2 General development of the sanctuary of Hera through the century culminated in the building of a treasury *c.* 700.
3 The Samian adventurer Kolaios discovered Tartessos (near Gadiz, on the Atlantic coast of Spain) c. 640. The poet Semonides led a Samian 'colonizing' venture to Amorgos, by which place he is usually known, c. 610. Samos-in-the-Nile was the Samians' base in Egypt before Amasis concentrated Greek 'trade' at Naukratis.
4 Syloson assumed power c. 590.
5 See Herodotus 3.39; Thucydides 1.13.
6 See Herodotus 3.54: the siege of 525 suggests that the walls at least were completed by that time.

7 Called Mt Ampelos in Herodotus' time.
8 ὄρυγμα ἀμφίστομον.
9 πεντήκοντα καὶ ἑκατὸν ὀργυιάς. An *orguia* is the distance between the fingertips of a person with arms outstretched sideways, roughly equivalent to 6 feet and thus roughly equivalent to a fathom. We do not know which of several standards (if any) Herodotus was using, thus we cannot assess his accuracy. Standard measurements developed slowly and, like calendars and coin systems, could vary from *polis* to *polis*. For example, an *orguia* on the Attic standard foot is equal to 1.8 m; on the Olympian standard foot, it is 1.92 m. See e.g. Richardson (1985) 29–30. However, Herodotus' figures are highly likely to be his personal estimates, not measurements taken by him or the record of someone else's measurements.
10 One stade=600 feet.
11 This is a literal translation of the Greek, and not the British Imperial measure. All references to feet in this chapter are translations of Greek πούς or Latin *pes*.
12 ὄρυγμα.
13 εἰκοσίπηχυς; 1 cubit=the distance from elbow to fingertip.
14 τρίπουν τὸ εὖρος.
15 χῶμα.
16 τρία μέγιστα ἐξεργασμένα.
17 The list, compiled in Hellenistic times, is: the pyramids of Egypt, the Hanging Gardens of Babylon, the temple of Artemis at Ephesus (built in a bog), the Mausoleum at Halikarnassos, the statue of Zeus at Olympia, the Colossus of Rhodes, and Pharos lighthouse near Alexandria.
18 Kienast (1990) 41. On Herodotus' accuracy in measurements, see n. 9 above.
19 Occasionally it is higher than this, more often it is lower. The minimum from our sample of measurements was 1.47 m, and the maximum height, which occurs in the north tunnel at the junction with the south tunnel, we estimated at 3.5 m.
20 Hence the gradient is approximately 1 in 200, or 0.5 per cent.
21 See Kienast (1990) 41 and figure 4. However, it is not obvious to us that the failure to dig the channel down to depth was 'to save on labour and facilitate work'. On the contrary, it seems to us that digging the ditch to about 3.5 m *and* tunnelling through the bedrock several metres below the ditch represents a waste of labour, perhaps indicating an error in the ditch level. There are numerous unanswered questions about the water channel, for example: was it first dug on the wrong level, and then tunnelled at the lower level? Or was it tunnelled as the channel grew deeper in order to avoid the risk of the side walls collapsing into the channel?
22 Following Kastenbein's survey, Kastenbein (1960).
23 It is of course extremely difficult to orientate oneself in a tunnel. It is also extremely difficult to describe clearly and concisely an object like the tunnel. This may explain in part why the secondary literature is, or appears to be, misleading in a number of respects, especially concerning the relative straightness of the tunnel.
24 Hence the very high ceiling of the north tunnel at this point; it is clear from the abandoned face of the tunnel that it was being dug with the standard size and shape.
25 See Széchy (1966) 503f. The natural ventilation of the tunnel is excellent, so much so that the matter of ventilation might easily be overlooked by someone in the tunnel (and indeed is overlooked in the secondary literature).
26 Goodfield (1964) 112.

27 Goodfield and Toulmin (1965) 52.
28 This cliff (east of Tower 28) and the line of the tunnel are marked on the map insert in Kienast (1978). See also the sound arguments by Burns (1971), especially those on p. 178.
29 The cross is offset so as not to interrupt the line of sight between opposite plumb lines. Full descriptions and illustrations of all the tools can be found conveniently in Dilke (1971).
30 Going round the west end is the easiest and least error-prone route to take, notwithstanding the modern Greek army camp which blocks the route just south of the Roman aqueduct bridge (fieldworkers should beware the camp guard dogs). Burns (1971) suggests that the surveyors could have gone round the east end of the mountain, but the east route, besides being much longer, requires walkers to rise some 40 m to get over the pass between Kastro and the neighbouring mountain at the east end, so this route, like the poles-over-the-top method, would have required many more sightings and calculations (and involve many more errors) than the short west end route.
31 This is best seen in front of the Stratos Hotel off Kanari street, where the Byzantine harbour wall has been partially excavated.
32 As stated in the standard textbook on the subject, 'tunnel surveying is one of the most difficult chapters in engineering geodesy and differs from surveying on the surface in many respects', Széchy (1966) 524.
33 This can be found conveniently in Cohen and Drabkin (1966) 341f. with n. 1.
34 The dioptra was adopted for astronomical sightings, but there is no evidence that it was employed for surveying purposes.
35 We consider the calculation of numbers further, pp. 415–16 below.
36 See esp. p. 43f. Space precludes a detailed discussion of this adapted method here.
37 See esp. p. 43: 'This straight line [of poles] would have been beyond the supposed entrance or exit of the tunnel to ensure minute exactness and to facilitate *a line of projection into the tunnel*' (our italics).
38 The total distance between the bottom of the staircase and the start of the built section is about 15m.
39 See Széchy (1966) 107.
40 See Section 3 above for description and Figures 18.3 and 18.4.
41 This seems to be what one of Nonius Datus' two crews did—turn the wrong way. See 5.2 below.
42 We consider timing in 4.3.6 below.
43 And elsewhere: Eupalinos' home town of Megara, for example.
44 He also invented the plummet, lathe and lever, according to Pliny *Natural History* 7.198. Clearly a remarkable man, Theodores is also said to have constructed labyrinths, (with Rhoikos) to have invented a method of casting large bronzes, and worked in gold and silver (making the signet ring which Polykrates threw into the sea as his most valued possession, and received back in the belly of a fish, for example, Herodotus 3.41.1).
45 A.M.Snodgrass applied this memorable phrase to the traditional concerns of classical archaeologists, in Snodgrass (1984) 230; it can be applied equally to the concerns of some historians of science (and especially mathematics), among others.
46 This section was closed when we visited the site.
47 It is a reasonable further assumption that work went on round the clock. This will not affect the calculation.
48 Estimates vary from 5 to 15 years. See Jantzen, Felsch and Kienast (1973) and Mitchell (1975).

49 Distance per day=length of tunnel/(years taken×365). Thus, 620/1825=0.34 m/day.
50 620/3650=0.17 m/day.
51 5 years on the north tunnel minus 3.38 years on the south=1.62 year difference.
52 10 years minus 6.7 years.
53 (1.62×365)×0.34=201, or (3.3×365)×0.17=205.
54 365 (days)×0.34 (m/day)=124 metres.
55 1040-124=916 m to dig; @ 34 cm/day=2694 days=7.38 years. Alternatively, 1040-62=978 m to dig; @ 17 cm/day=5753 days=15.76 years.
56 No one has yet been able to find evidence of such a shaft, and the argument that the top of the shaft was deliberately hidden because it was outside the city walls will not work for the bottom of the postulated shaft inside of the tunnel, where there was no reason to hide it. Likewise the argument that the tunnel lining at the north end may have masked the bottom of the shaft is a poor one. The (Roman) lining starts some 22 m in, whereas the shaft at the south end is about 18 m in. So the postulated shaft, for which there is no evidence inside or out, would have to have been built at least 4 m further in (and up the mountain) than at the south end.
57 Hence the surveying marks 'in the tunnel' referred to by Kienast (1990) 45? Further discussion of them can be found in C.Ptinis (N.D.) 46, 48.
58 Although there are no other water works comparable in *sophistication* to Eupalinos' tunnel—even in Roman times, there are in the same period (C6 and C5 BC) a number of underground waterworks of considerable size and quality—so much so that miles of conduits built entirely underground in the C6 in Sicily are still in use, supplying water to the populace of modern Siracusa, for example. Other installations using the same techniques, materials of construction, and dimensions, have been found at, for example, Megara, Lindos, Olynthos and Corinth. As Burns notes (1974:405), this indicates that there already existed in the C6 a well-developed profession with established traditions, standards, and methods, and that some of these survive to Vitruvius.
59 By Mytilenean prisoners of war: see Herodotus 3.39.
60 In the eastern portion of the isthmus between Athens and the Peloponnese, in mainland Greece.
61 We will not here address the issue of working conditions for Eupalinos' tunnellers, or their status. But see Pliny *Natural History* 31.70–1 for comparative material: 'by the light of lamps, long galleries are cut into the mountain. Men work in long shifts measured by lamps, and may not see daylight for months on end…the roofs are liable to give way and crush the miners, which makes diving for pearls or getting purple-fish from the depths of the sea seem comparatively safe. So much more dangerous have we made the earth…the miners carry the excavated material out of the workings on their shoulders, each man forming part of a human chain working in the dark; only those at the end of the line see daylight' (Penguin trans.).
62 The only three trade-names referred to in the Epidauros inscriptions are the excavator (ὀρυκτάς), the plasterer (κονιατήρ), and the assistant (ἀρωγός); Burford (1969) 198.
63 See Xenophon *Cyropaedia* 8.2.5.
64 See Burford (1969) 35: 'many of the workmen…came from elsewhere, at virtually every stage of the scheme'.
65 See Cartledge (1979) 142–4, 158–9, and 231; and Shipley (1989) via the index.
66 Burford argued (cogently, and it is particularly relevant here in view of the Samians' reputation for piracy and kidnapping) that craftsmen would be more likely to work

in a foreign state if some sort of agreement (on legal rights, for example) existed between the craftsman's home *polis* and his current place of work. On the other hand, craftsmen might have left their homelands more or less voluntarily and for numerous reasons, and found Samos an agreeable, or at least tolerable, place of residence in this period.

67 Later Polykrates was said to have paid (unspecified) high wages to immigrant craftsmen, Alexis *FGH* 539 F 2.

68 See Burford (1969) 197 and table IX.

69 The works cannot be dated more precisely than the second and third quarters of the sixth century. Attempts to narrow the dates are based on more or less speculative and more or less plausible contexts to provide motives for their construction. Shipley's attempt (1989:74–80) to attribute the walls, tunnel and breakwater to Polykrates (and push back Polykrates' accession to the 540s in the process) is unconvincing, and appears to be motivated by a misreading of Aristotle *Politics* 1313b24: τῶν περὶ Σάμον ἔργων τὰ Πολυκράτεια, which should be translated 'the Polykratean *part* of the works around Samos' (a partitive genitive, so Barker), not 'the Polykratean works around Samos'.

70 Besides preying on Spartan gift-exchange traffic with Lydia and Egypt, and abducting Corinthian hostages en route to Lydia, during this excursus we are informed of a number of other specific actions by Samians: Mytileneans (seized after a naval battle) working in chain-gangs on the moat, a Samian attack on Egypt (the Samians had their own base in Egypt, Samos-on-the-Nile, which they were forced to give up when Amasis 'concentrated Greek trade' at Naukratis), Samian exiles plundering Siphnos and then northern Crete, and Samian raids on Aigina.

71 Miller (1971) 24.

72 See Trevor Hodge (1989), especially p. 129.

73 See Burns (1974), especially 405.

74 Rather than because of his beautiful and subtle mathematics.

75 *Marcellus* 17, Penguin translation.

76 He says in his preface, 'I deem it necessary to expound the method partly because I have already spoken of it [*Quadrature of Parabola,* preface] and I do not want to be thought to have uttered vain words, but equally because I am persuaded that it will be of no little service to mathematics; for I apprehend that some, either of my contemporaries or of my successors, will, by means of the method when once established, be able to discover other theorems in addition, which have not yet occurred to me. First then I will set out the very first theorem which became known to me by means of mechanics…' (Heath translation).

77 Sarton (1959) 78.

78 *On Architecture* 9.Preface.l5, our italics. For example, Vitruvius cites Pythagoras' theorem as 'particularly serviceable in the building of staircases' (9.0.7). Vitruvius was writing a handbook of the 'how to' variety for practical application by anyone who had anything to do with building of any sort, which includes, for example, testing the quality of water, the proper and the slapdash way to make the colour black, and how to make and where to put inverted bronze (sounding) vessels around a theatre to 'increase the clearness of sound (of the voice) and awake a harmonious note in unison with itself' (5.5.1–3). The last is fully informed by understanding and discussion of the (mathematical) theories of acoustics and harmonics and their anciently perceived relevance to the serious business of theatre-going and audibility therein.

79 *Natural History* 36.121, our italics.

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