Foundation Engineering

Lecture #01

Roman Engineering

- Roads
- Arches, vaults and domes
- Bridges
- Aqueducts and sewer systems
- Tunnels

L. Prieto-Portar, 2009

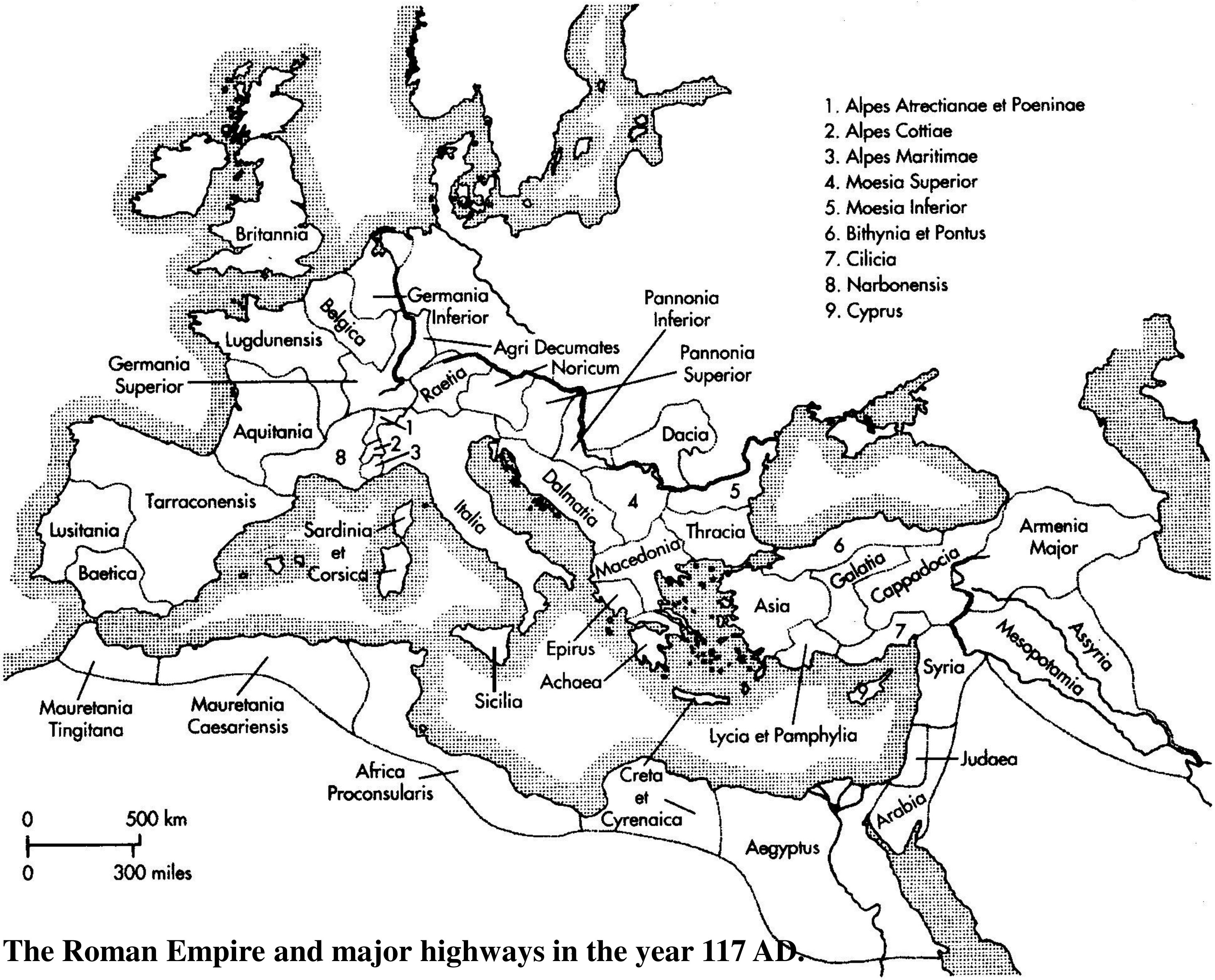
ROMAN ROADS.

The earliest Roman roads were probably little more than tracks, mainly along river valleys in Italy, some following prehistoric lines of communication. The Etruscans had already constructed a network of well-built roads connecting their settlements, and some of their towns had paved streets.

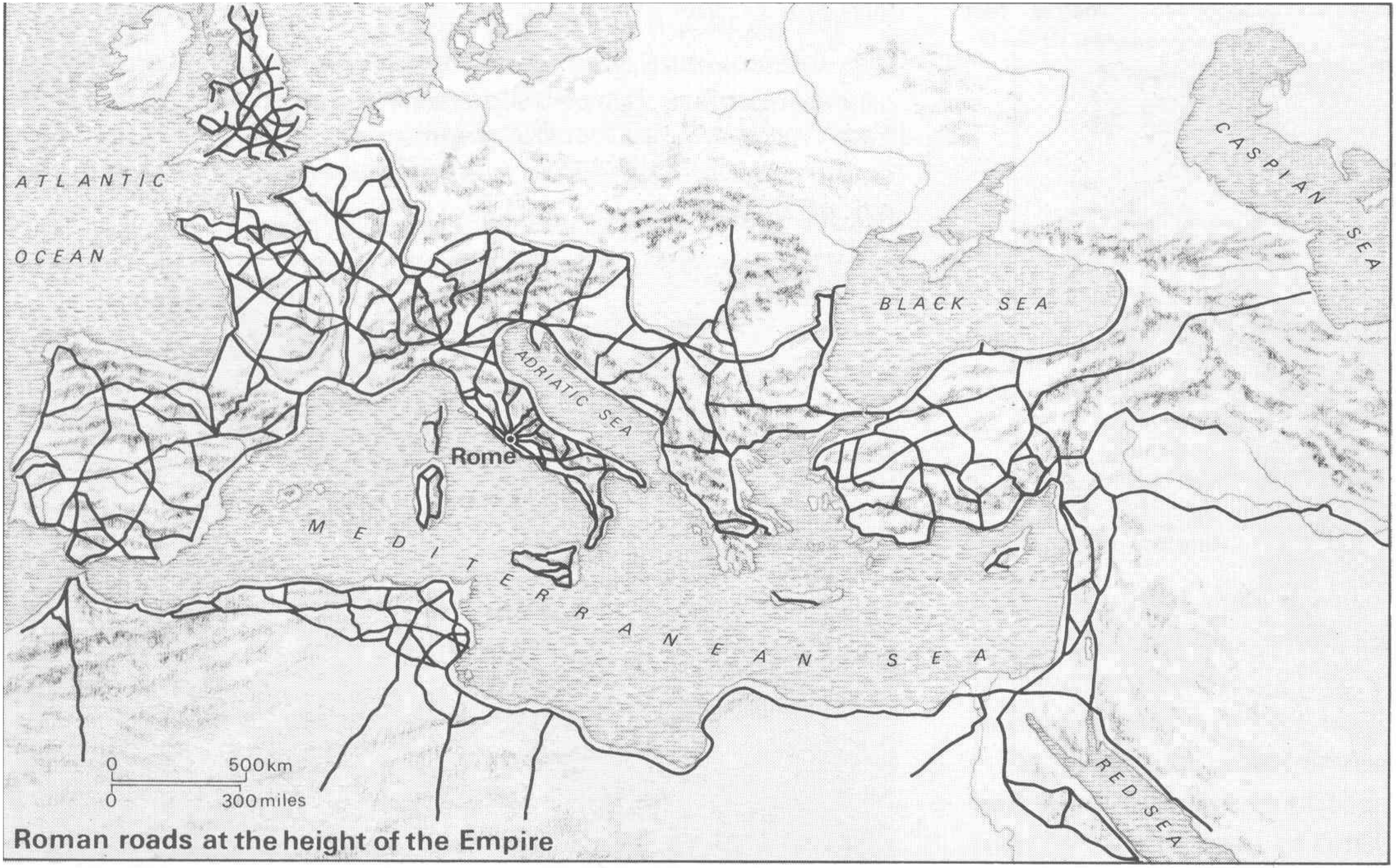
The Romans developed upon the road-building skills of their Etruscan and Greek predecessors. From the late 4th century BC they began to undertake the construction of major roads. These roads were relatively straight, with good foundations and surfaces, and where necessary they had tunnels, embankments and bridges.

Roads were initially constructed for military, and not economic reasons. Their prime function was to facilitate the movement of troops and to link Rome with its colonies for efficient communication and administration. The main consideration was to provide a firm footing for infantry in all weather conditions. Vehicular traffic was secondary, and therefore, steep gradients were sometimes used.

These strategically important military roads (*viae militates*) came to be used increasingly by the civilian population, and therefore led to an expansion of trade and the rapid spread of prosperity, Roman ideas and their way of life.



The Roman Empire and major highways in the year 117 AD.



The Roman 90,000 km highway network in 330 A.D. were all provided with high quality surface (*pavimentum* or *summa crusta*).

Roman Road Engineers.

During the Roman republican era, the construction of roads was the responsibility of magistrates (censors, consuls or provincial governors), who let out contracts for new roads. On the other hand, maintenance such as resurfacing, paving and cleansing were the responsibility of *aediles*. The public main roads were known as *viae publicae*, *viae praetoriae* or *viae consulares*.

In 20 BC a board of officials (the *curatores viarum*), was set up to manage state highways. No *curatores* of provincial roads are known, but governors acting through local authorities were responsible. Contractors were paid with money from the treasury, by the emperor, from local authorities and from landowners. The maintenance of the main roads was always a problem, and for many roads a special curator was appointed for this purpose.

The actual builders of the strategic roads were *army engineers*. They were helped by both army and civilian workforces. Little is known of how the work was organized, but some inscriptions give sketchy information.

Roman roads came to be constructed throughout the empire, and under the emperor *Diocletian*, 372 main roads (90,000 km) were recorded.

Road Construction.

The main Roman road system took the form of twenty-nine great military roads centered in Rome. The Roman Empire extended over eleven regions (with present-day countries in parenthesis): *Italia* (Italy), *Tarraconensis* (Spain), *Gaul* (present-day France), *Britannia* (Britain), *Illyria*, *Thrace* (present-day European Turkey), *Asia Minor*, *Pontus* (Turkey), *Armenia/Syria/Mesopotamia/Assyria*, *Aegyptus* (Egypt) and *Numidia/Mauretania* (North Africa).

These regions were divided into 113 provinces traversed by 372 great roads totaling 52,964 Roman miles. The greatest of these roads, as a piece of engineering was the *Via Appia* which extended for 500 km, of which 200 km was paved with large slabs of stone, each squared and fitted exactly. The remainder was paved with fitted polygons of lava. The Appian Way was commenced by *Appius Claudius* (after whom it was named), and who built 200 km. It is believed to have been finished by *Julius Caesar*.

The Romans even had the equivalent of the modern highway textbook, the "*Itinerarium Antonini*" compiled about 200 AD. This book comprises an itinerary, setting out the military stations on the principal roads and the distance in Roman miles along them. A Roman mile was a thousand military paces (*milia passum*), a *passus* being measured by the position of the rear foot at the beginning of a pace to the position of the same foot after taking it, a distance slightly under 5 feet, making the Roman mile approximately equal to, or a little less, than an English mile.

The *Via Appia* in the outskirts of Rome. It was originally built in 312 BC to Capua, and then extended it was extended to Brundisium (present day, Brindisi) on the Adriatic Sea.

Present day *Via Appia* at *Capua*, close to *Pompeii* (east of present day *Napoli*).

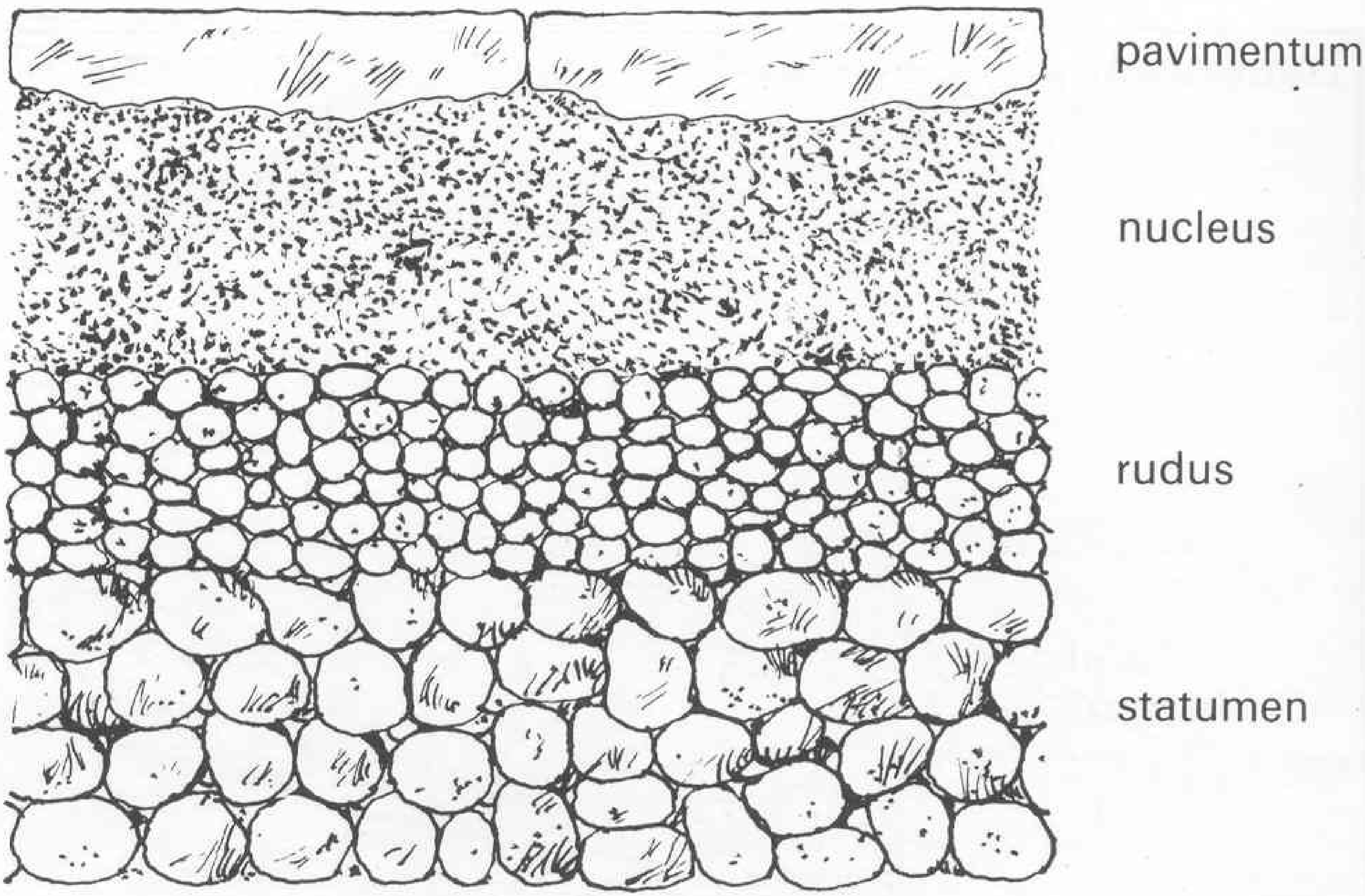
Roman roads are generally considered to be wide and straight, but this was the case only where terrain was suitable, such as in Britain. Many Roman roads survive today, and the ones that have been excavated show that there was no standard design.

Roman engineers were well aware of different soil conditions and constructed roads using use local materials, even iron slag. The strip of land for the road was first marked out by furrows, and a road trench was dug to bedrock or to a firm foundation, often fairly deep (*up to 1.4 m*). The roads were built in sections, and the first stage was to reinforce the foundation by ramming piles or brushwood. Successive layers of foundation materials were then built to assist in draining the road. Across marshland, the foundations often consisted of a raised embankment made with a timber framework secured by vertical piles from tree trunks. Some main roads were built on a raised embankment (*agger*).

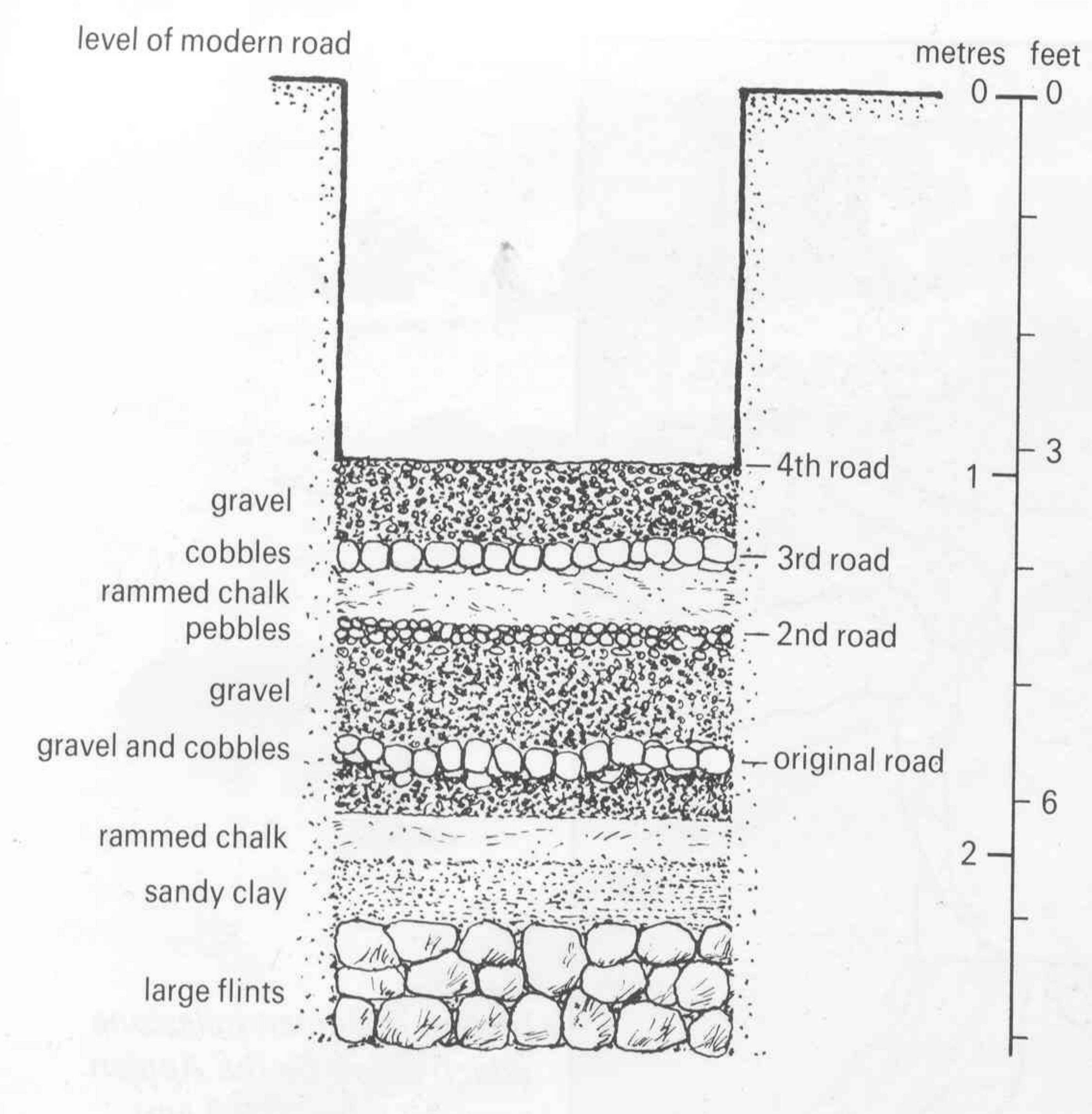
Over the foundations the surfacing material varied, from gravel to pebbles to cut stone slabs, such as the streets in *Pompeii* as seen today. The paving stones were held in place on each side of the road by a stone curb (*umbo*). Most roads were cambered and had side gutters or ditches to assist drainage. Some ditches were originally quarry ditches dug to obtain material for the road construction, while others acted as boundaries.

The typical section of a Roman road is shown on the next slide. The width of roads was commonly 4.5 m to 5.5 m, but varied greatly, from about 1.2 m to 9.1 m. According to the *Laws of the Twelve Tables*, roads were supposed to be 4.8 m wide in order to allow two vehicles to pass. Decrees issued by *Augustus* stated that the *decumanus maximus* must be 12.2 m wide and the *cardo maximum* 6 m, with other roads 2.4 m, but in reality widths of roads varied according to their status. In towns, openings through surviving gateways indicate the width of their roads.

The Romans constructed their roads in several layers, building them up to a causeway, thus achieving the drainage necessary for all the year round use. Before a road of the highest class was made, two parallel trenches were cut along the intended edges of the formation and, between these, all the top-soil and loose material was removed down to hard ground (a firm foundation). This excavated cut was then filled in with fine, dry earth well rammed in, forming a layer called the *pavimentum*. On top of the pavimentum came the next layer of small, squared stones, either left dry or with mortar poured in to form a watertight course, called the *statumen*. On this was laid the *rudus*, or *ruderatio*, a kind of concrete consisting of one part of broken stones to two parts of lime. The *nucleus* was the next layer, and was a lower grade of material made of lime, chalk and broken tiles, or gravel, or a mixture of sand, lime and clay. In fact, whatever local material could be made to consolidate into a hard, permanent mass was adopted. The topmost (wearing surface) was called the *summum dorsum*, made from large stone slabs, carefully fitted together. The *summum* had a 2% slope to the sides to drain rainwater.



Vitruvius wrote about Roman road specifications, shown in profile above with over 1 meter in thickness (compare to present day 0.60 meters).



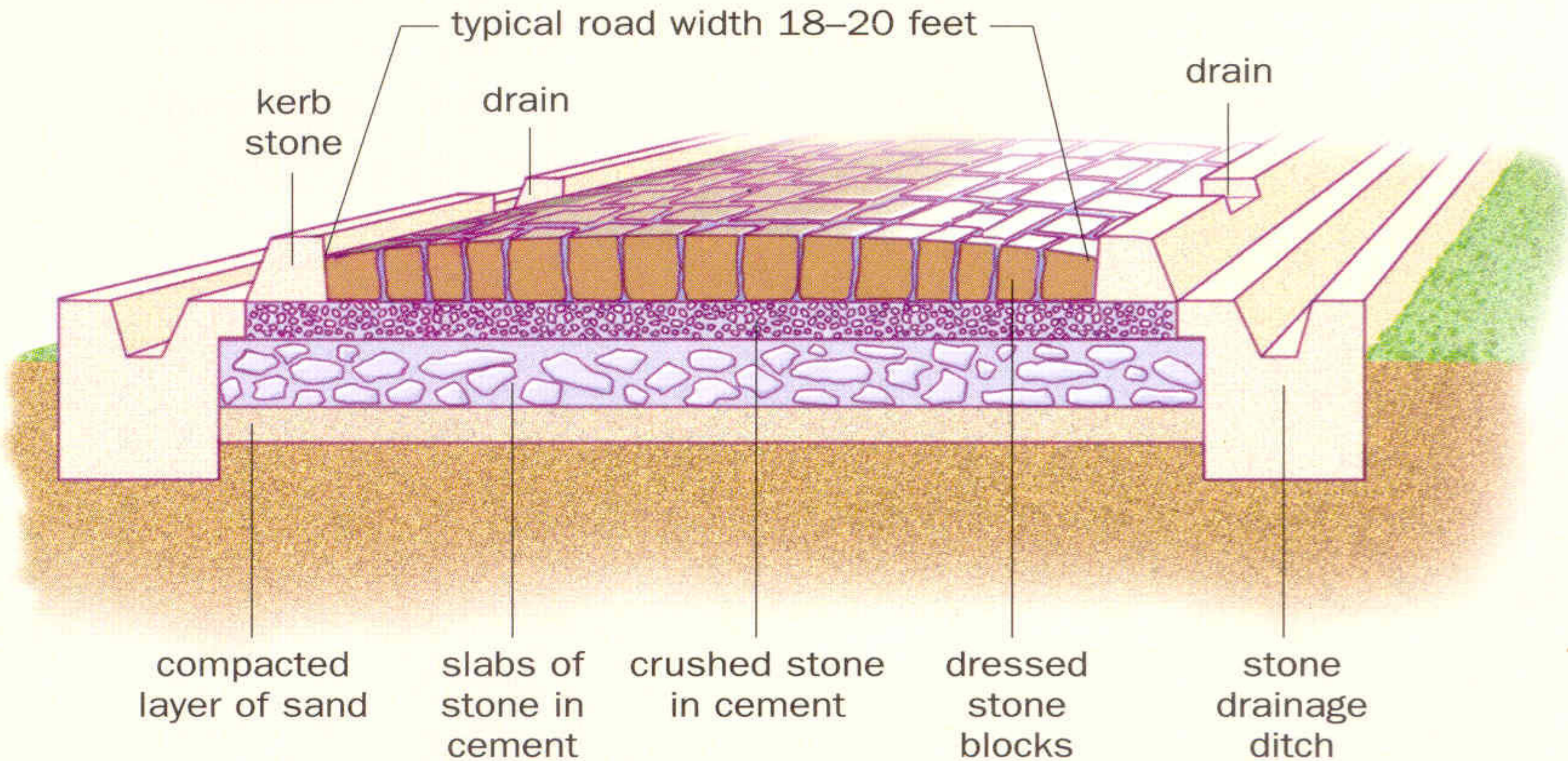
A Roman road built in Britain, currently called Watling Street in Rochester, shows the original Roman road, and three younger British roads on top.

Finally, the wearing surface, or pavement, called the *summum dorsum* or *summa crusta* consisting of fitted stones like flagstones, rectangular or polygonal in shape, or, in the case of roads of less consequence, a wearing surface of a gravel and lime concrete. These layers raised the road surface well above the surrounding ground level, forming a causeway known as the *agger*.

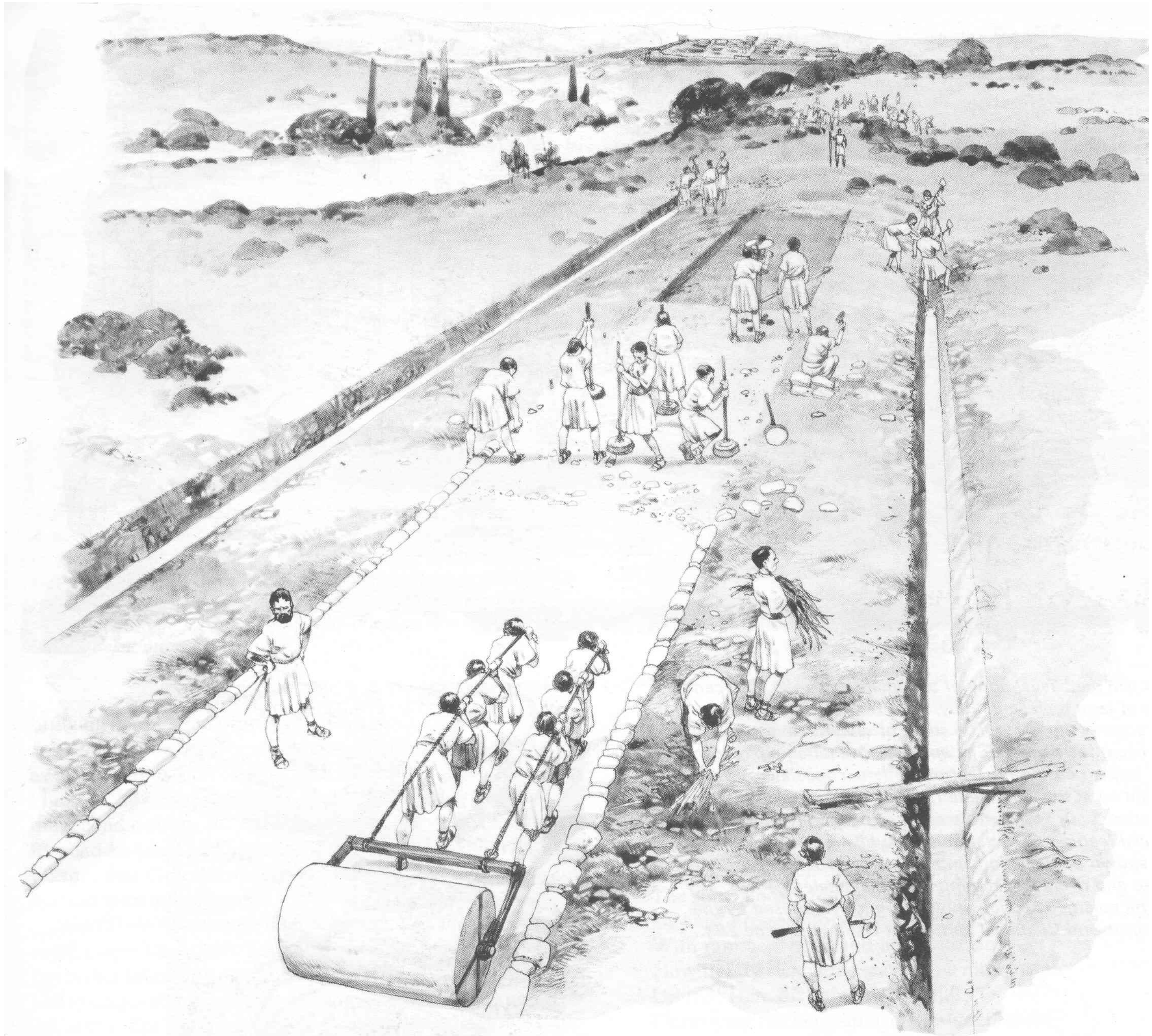
Great care was taken to keep water out of this formation by cambering the top surface and by cutting drainage ditches along the edges of the road. By such means the Romans provided roads which, even in countries subject to wide variations of weather, have lasted 2,000 years and even now are, for many hundreds of kilometers are the foundations of modern highways carrying traffic far beyond anything the builders could have imagined.

Minor roads were much less carefully constructed than major highways. They were mainly cross-country tracks used by traders and local roads and private ways leading from rural settlements to the main highways. Very few would have been constructed with firm surfaces, and they are difficult to locate and record.

Roman roads were constructed of four *strata* (layers, from which the word "street" is derived) to a depth of between three and six feet. Roads were cambered, or raised in the middle, for drainage and thus never became mired in mud. There was frequently sufficient space for one cart to pass by another, but no one knows if traffic was compelled to travel on the right- or left-hand side of the road.



The profile of a typical Roman road was already perfected by circa 50 BC.

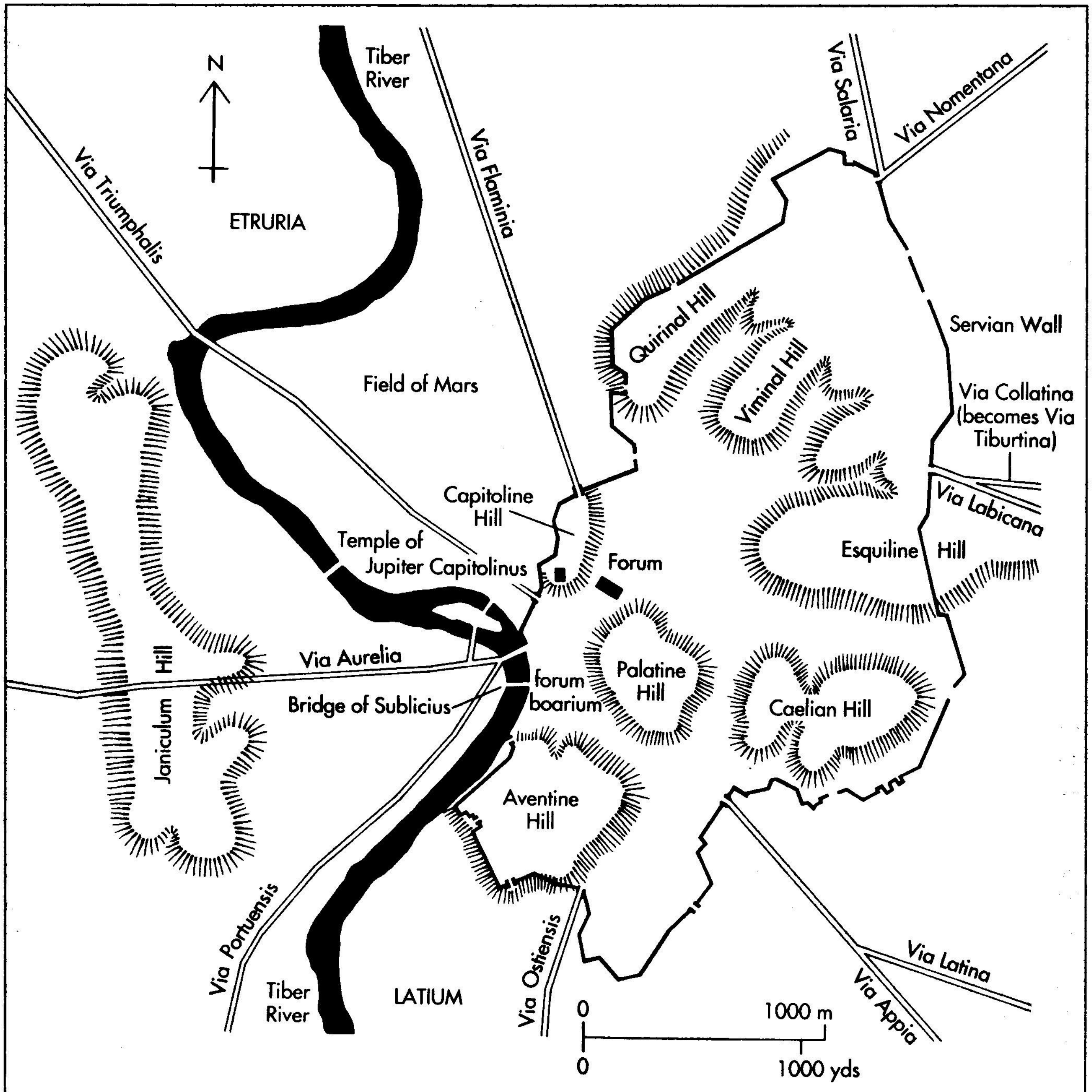


This drawing shows the surveyors ahead, followed by a crew digging the fossae to drain the soil, then hand tampers forming the statumen, rudus and nucleus. Each is compacted by the crews shown in the fore-ground (from *Roman Engineers*, L.A. Hamey 1981).

Roman Road Names.

Few of the original names of the Roman roads are known except for those in Italy. In the republic, roads were often named after the magistrate (usually the censor) who was responsible for their construction. For example, the *Via Appia* was named after the censor *Appius Claudius Caecus*. In northern Italy the *Via Flaminia* was named after the censor *C. Flaminius*; and the *Via Domitia* from the Rhône to Spain was named after *Cn. Domitius*. The *Via Egnatia* was the main road east from Italy that crossed Thessalonica (today's Greece).

Roads tended to radiate from the center of towns toward neighboring towns and might be named according to the town to which they led (such as *Via Ostiensis*). Gateways in town walls often bear the same name as the roads passing through them (such as *Porta Appia*, *Porta Ostiensis*, *Porta Aurelia*).



Rome in the year 44 BC, showing the seven hills and the road system.

Roman Road Types.

The Latin names for roads and streets were various and originally of rural origin but came to be applied to urban situations as well. Examples include:

- ***actus*** : a local road or track for animals and vehicles, probably forming a large part of the communication network. Originally meaning a right to drive cattle (from ***agere***, to drive cattle).
- ***agger*** : a causeway forming a road.
- ***angiportus*** : a narrow street or alley.
- ***callis*** : a track, especially for seasonal use.
- ***clivus*** : street on a slope.
- ***crepido*** : a pavement.
- ***iter*** : a route; right of way; path for travelers on foot, horsemen or litters.
- ***limes*** : a path or track, often acting as a boundary; a fortified frontier line.
- ***pervium*** : a thoroughfare, passage.
- ***platea*** : a street.
- ***semita*** : a narrow path, lane.
- ***strata*** : an embanked road. From the 3rd century, it replaced the word ***via***.
- ***trames*** : a cross-way, footpath, path.
- ***via*** : a road for vehicles; street.
- ***vicus*** : the normal word for a city street, lane or district.

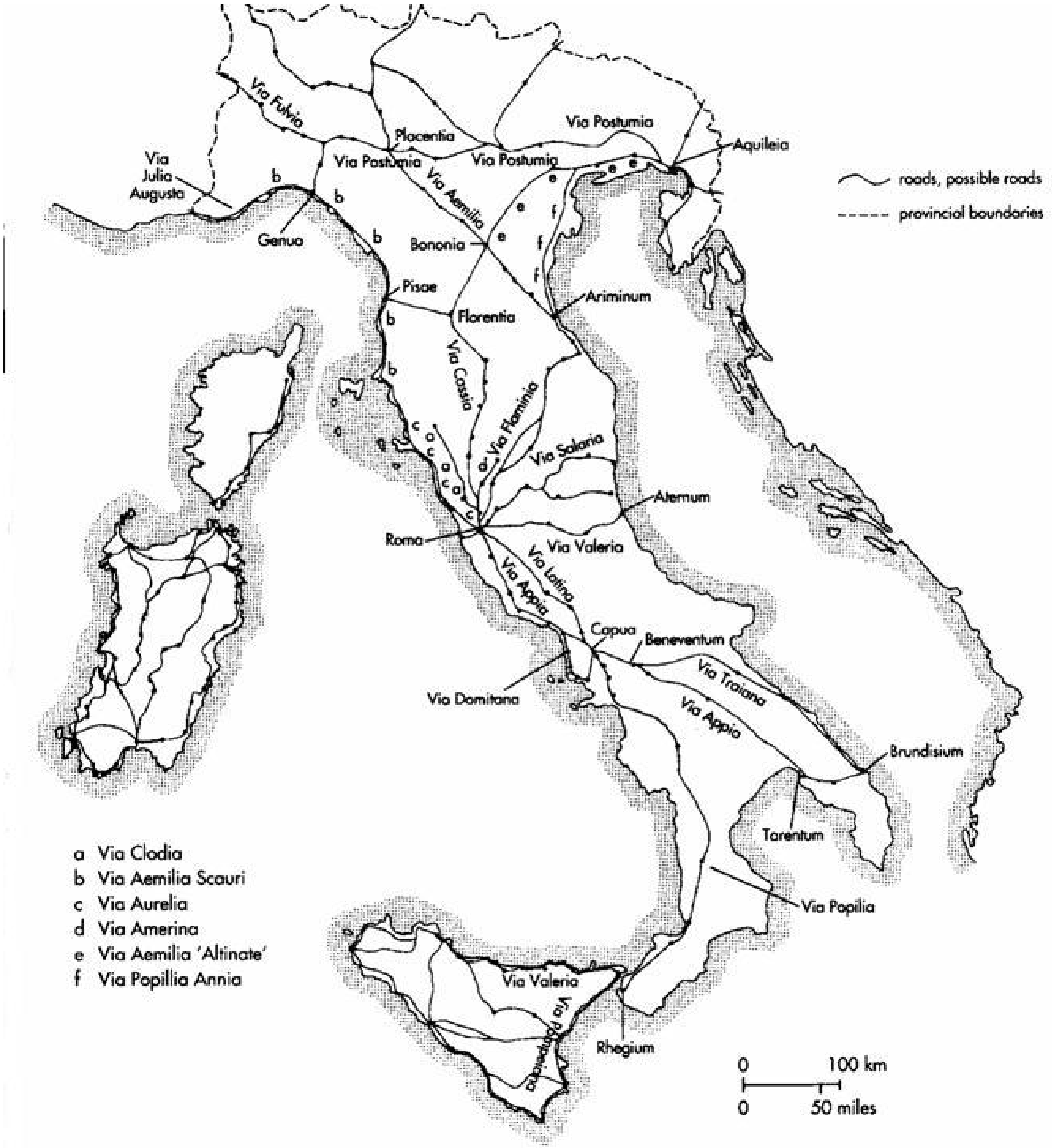
Roads in the Roman World.

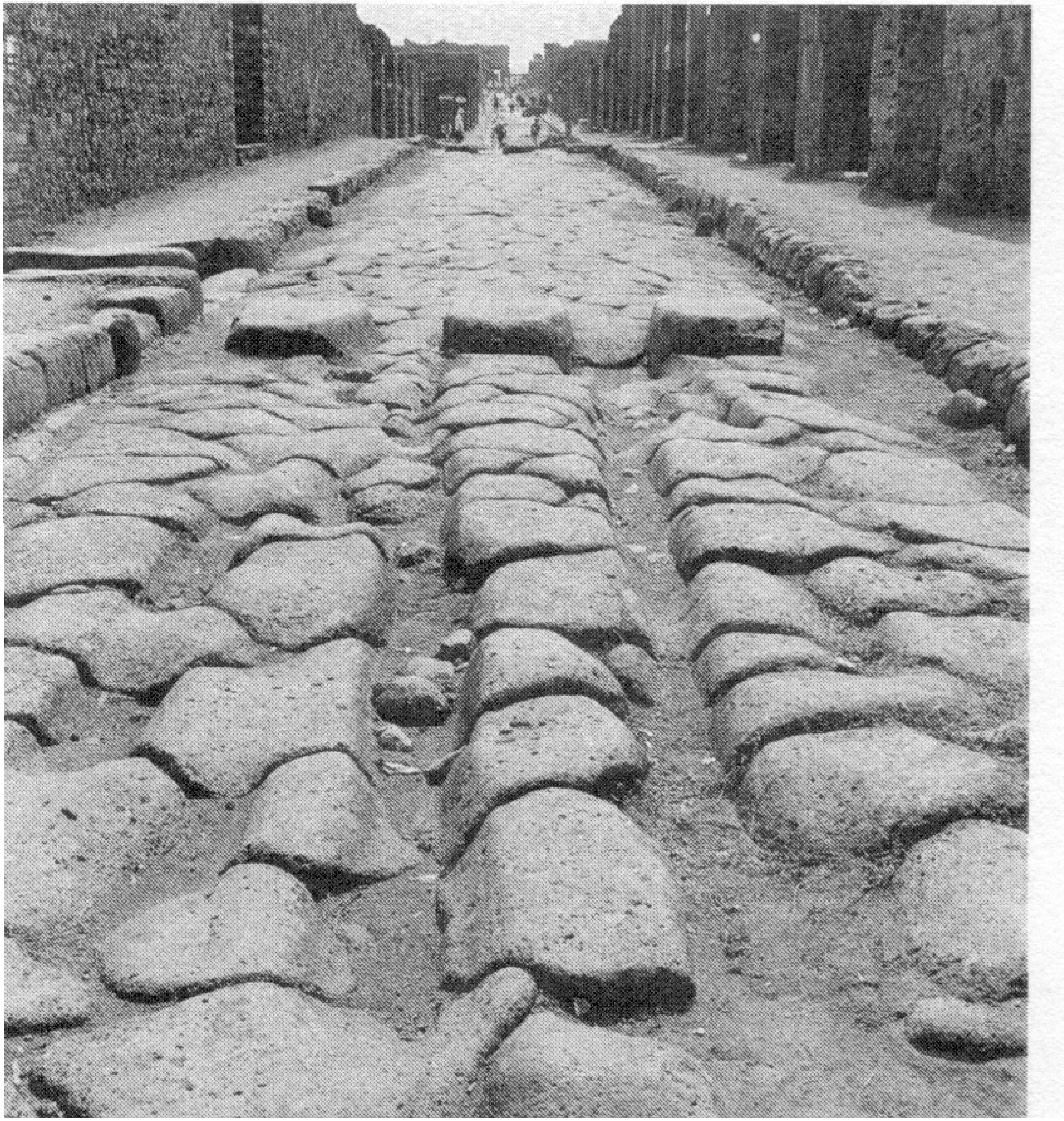
Roads developed with the conquest of territories and the setting up of colonies. Under the empire, the road system expanded greatly, extending into Asia, to the Euphrates and the Red Sea. From about 200 AC the pace of road building declined, and by the 4th century AC, the state was having increasing trouble maintaining roads.

Roads in Italy. The Appian Way (***Via Appia***) was the first well-constructed road, built in 312 BC from Rome as far south as Capua. Figure 2 shows a photograph of the Via Appia in the outskirts of Rome. Around 288 BC, it was extended to Benevento, and around 244 BC to Brindisi (the embarkation port for ships to Greece).

Roads probably built in the 3rd century BC include the ***Via Latina***, which rejoined the ***Via Appia*** at Casilinum near Capua. The ***Via Amerina*** originally led from Rome to Nepi and later to Falerii Novi and beyond. The ***Via Valeria*** initially went from Rome to Alba Fucens. The initial stretch of road from Rome to Tivoli was also known as the ***Via Tiburtina***. The ***Via Valeria*** was extended to Aternum by Claudius and was also know as the ***Via Claudia Valeria***. ***The Via Salaria*** (Salt Road) from Rome to Reate was on the line of an old trade route. After 16 BC it was extended to the Adriatic to Casuvm Trueninum. The ***Via Aurelia,*** shown in Figure 6, may have been constructed around 241 BC, and in 109 BC it was extended from Vada Volaterrana by the ***Via Aemilia Scauri*** as far as Genoa, and then by the Via Julia Augusta to the ***Via Domitia*** in Gaul.

The Roman road system in the Italian peninsula by the year 117 AD.





Paved street in present day Pompeii shows stone curbs, sidewalks and stepping stones.

The slots in the stepping stones show the two lanes used by the chariots and freight wagons.

Roman engineering affects our daily engineering more than most people realize. Consider this:

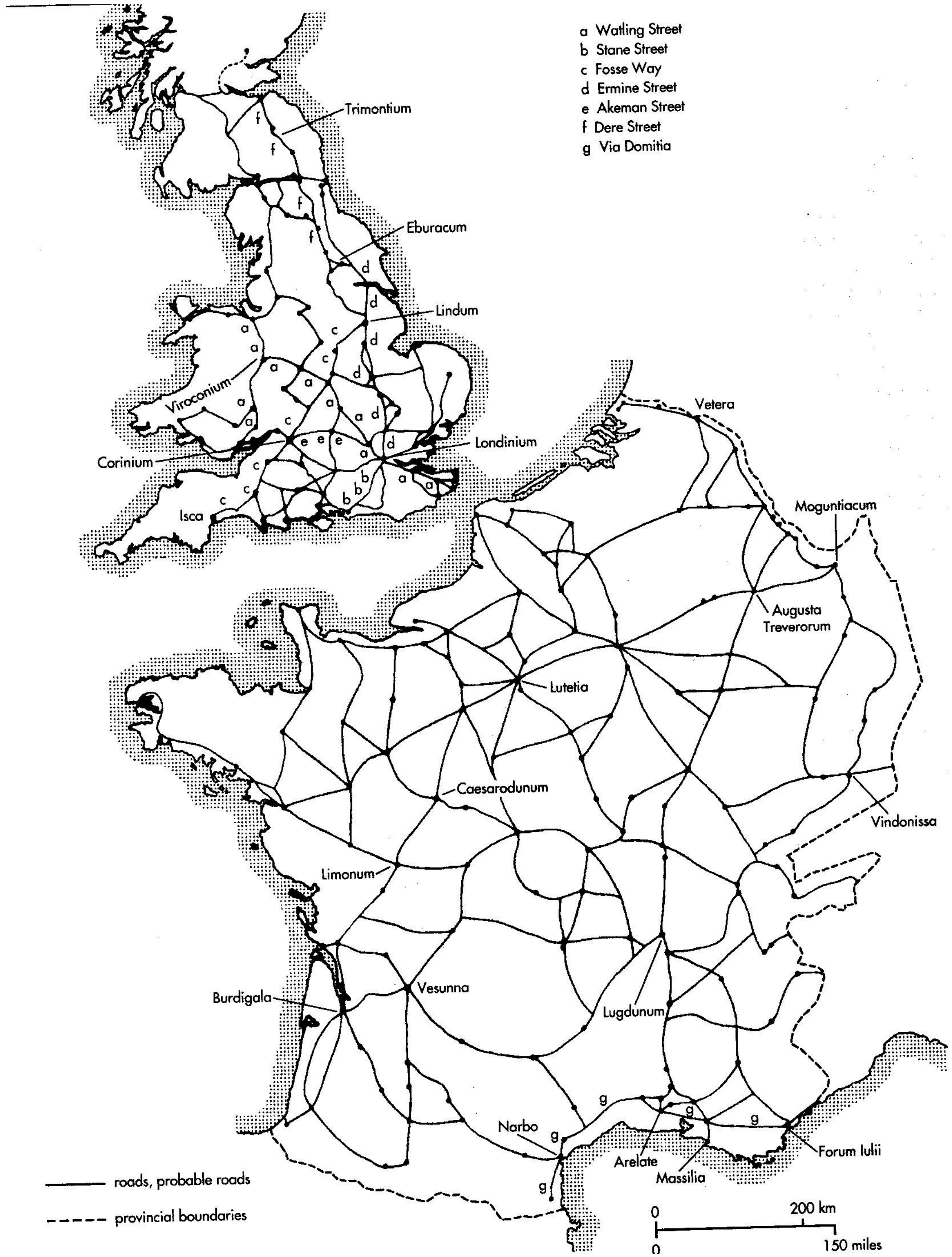
U.S. standard railroad gauge (the distance between the steel rails) is 4 feet 8.5 inches. The reason for this very odd number is because the English built their railroads at this gauge, and then came to the United States to build ours.

The English used 4'- 8.5" because that was the gauge for their older horse-pulled tramways. The people that built the tramways used the same jigs and tools that were used to build the even older horse-driven wagons. These wagons used England's old, long-distance roads, built by the Romans nineteen centuries before. Most English roads were rutted to their wheel spacing of 4'- 8.5".

Rome built the world's largest road system to accommodate war chariots. These chariots were pulled by two war horses. The two horses were hitched side-by-side, and the outer width of their "back ends" was, 4'- 8.5".

Therefore, our modern rail systems are based on Roman horse's rear ends.

La *Via Ostiensis*, leaves Rome westward towards the Roman port of *Ostia*.



The Roman road system in Gaul and Britannica.

The second main phase of road construction began with the ***Via Flaminia***. It was built from Rome to Fanum Fortunae and to Rimini in 220 BC. It diverged into two roads at Nami, converging beyond Fobgno. The ***Via Flaminia*** was restored several times, in particular by ***Augustus***. In 187 BC it was extended from Rimini to Placentia by the ***Via Aemilia***.

The ***Via Aemilia*** (or ***Via Aemilia 'Altinate'')*** was built from Bologna to Aquileia in 175 BC.

The ***Via Cassia*** was built about 154 BC from Rome to Florence and Pisa. It was paved in the time of ***Augustus***, having previously been a gravel surface.

The ***Via Postumia*** was built in 148 BC from Genoa to Aquileia. The ***Via Popillia Annia*** or ***Via Popillia***, built in 132 to 131 BC, ran from Rimini to Aquileia and carried the name of both its builders.

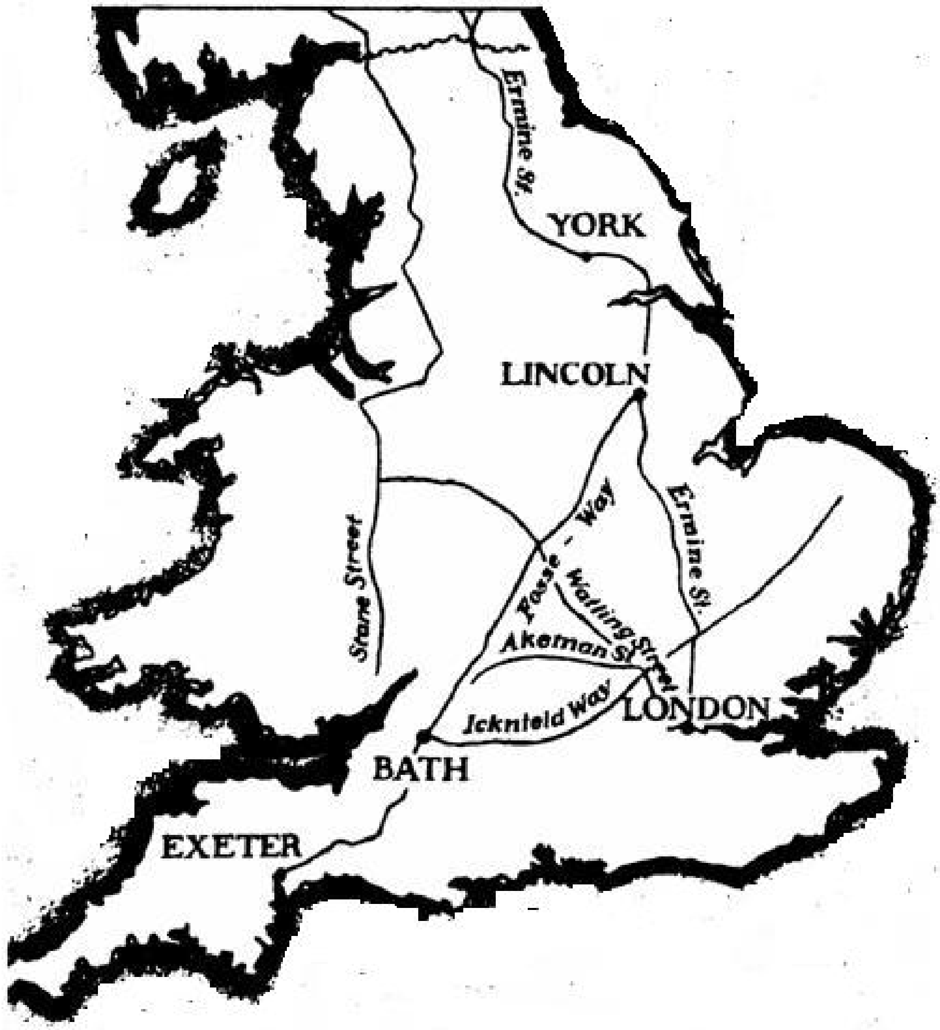
The ***Via Fulvia*** (125 BC) ran from Dertona to Hasta and later Turin. The ***Via Popillia*** extended the ***Via Appia*** from Capua to Rhegium. It is often incorrectly attributed to Popillius, who built the ***Via Popillia***, and through this confusion it is sometimes called the ***Via Annia***. The ***Via Clodia*** probably followed the same alignment as the ***Via Cassia*** to near Veii and then turned northwest to Satumia.

The ***Via Domitiana*** led off the Via Appia at Sinuessa across marshy ground to Cumae, Puteoli and Naples. It was built in 95 BC by ***Domitian*** to avoid the longer route via Capua, and was 79 km in length. The ***Via Traiana*** was built from Benevento to Brindisi as an alternative shorter route to the ***Via Appia*** by ***Trajan*** from 112 to 117 AC.

Roman Roads in Britain.

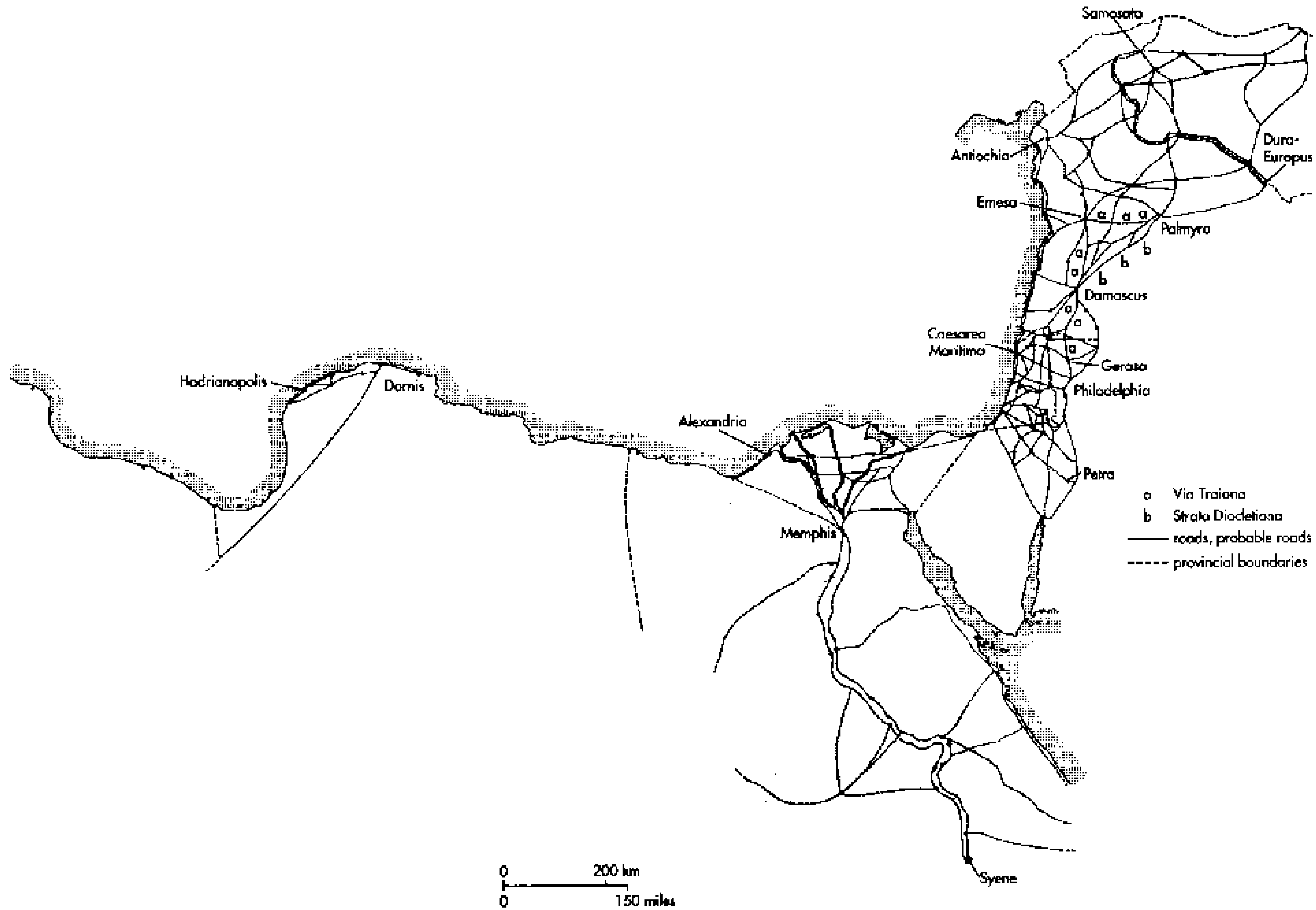
In Britain the road system dates back more than 3,000 years, the network of the Bronze and Iron Ages being still traceable. The country at that time was almost entirely covered with forest, and only the high uplands were free from thick undergrowth. The ridges, or watersheds, thus became the trade routes, and along them for centuries an interchange of trade and ideas took place. Along these roads settlements developed; man fought, bred cattle, worked with tools and worshipped gods.

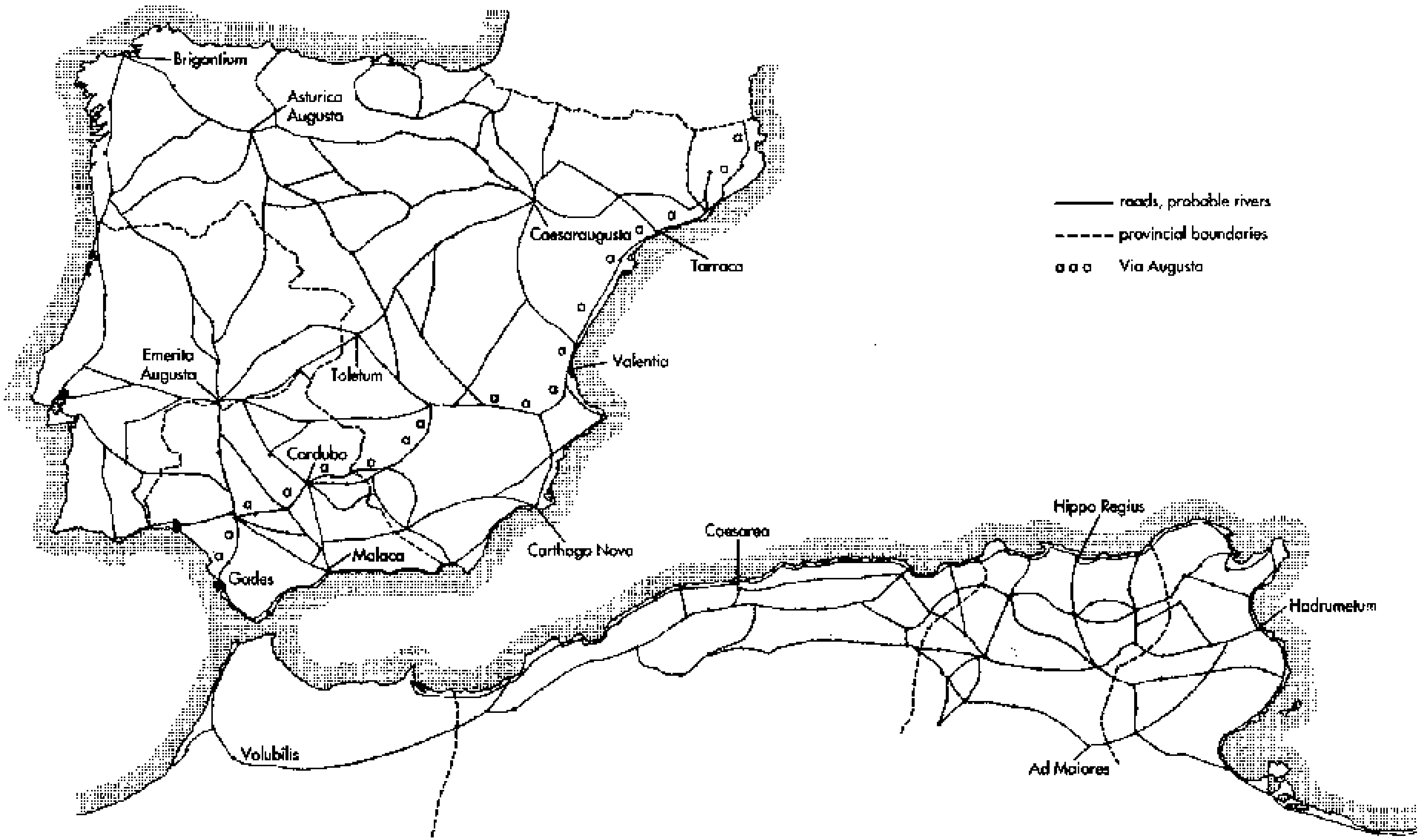
The road intersections became places of importance and around them leaders of thought and religion tended to congregate; thus at such intersections we find great monuments like Stonehenge and Avebury. Around these places great men were buried under mounds which, like the monuments, were examples of civil engineering. Their settlements were surrounded by earthworks for defense and for the security of their beasts. Only by even greater civil engineering works could the traces of the lives of these people be removed from the earth and thus the ridgeways, such as the Harrow Way, the Lun Way and the Fosse Way, remain to tell us of those early road users. However, it was the Romans that, in order to expansion their Empire, were the first great road engineers in Britain. To them, engineering was a vocation leading to high office in the state and one which competed with military art for the attention of the rulers. The military importance of roads led to high standards of construction and maintenance, even in the outer fringes of the Empire. The pattern of military occupation of countries like Britain consisted largely of garrison towns, built and run on Roman lines, connected by a highly organized system of communications depending mainly on roads.



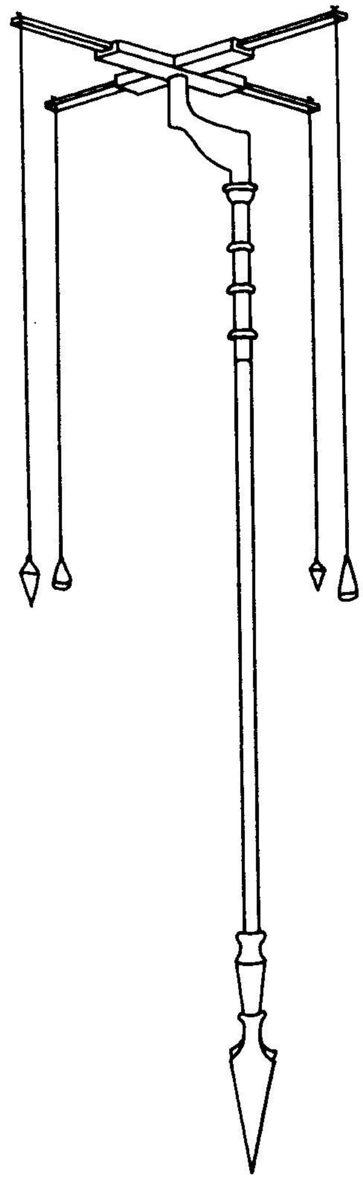
A system of military roads *in Britain was established by the Romans during their four centuries of occupation. It was based on a pattern of four main road groups radiating from London and a fifth running across the country between Exeter and Lincoln.*


a Via Egnatia
b Royal Road
roads,probable roads
provincial boundaries
Augusta Vindelicorum
Carnuntum
Aquincum
Tergeste
Apulum
Singidunum
Salonae
Novae
Odessus
Dyrrachium
Thessalonica
Apollonia
Serdica
Byzantium
Pergamum
Sardis
Ancyra
Melitene
Ephesus
Olympia
Athenae
Seleucia
0 200 km
0 150 miles


Samosata
Dura-Europus
Antiochia
Emesa
Palmyra
Damascus
Caesarea Maritima
Gerasa
Philadelphia
Petra
Alexandria
Memphis
Hadrianopolis
Darnis
Syene
a Via Traiana
b Strata Diocletiana
roads, probable roads
provincial boundaries
0 200 km
0 150 miles



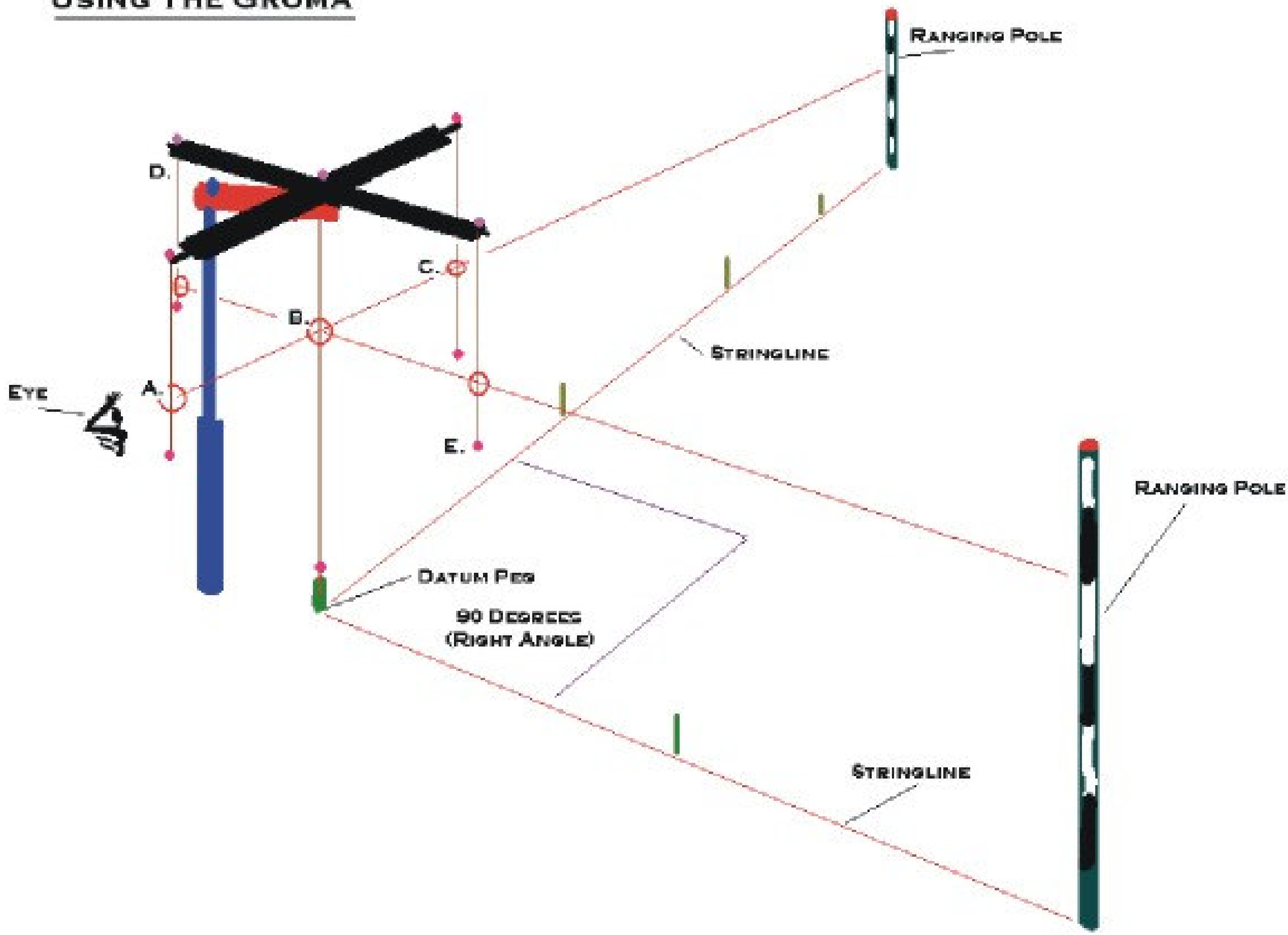
roads, probable rivers
provincial boundaries
Via Augusta
Brigantium
Asturica Augusta
Caesaraugusta
Tarraco
Valentia
Emerita Augusta
Toletum
Corduba
Carthago Nova
Malaca
Gades
Volubilis
Caesarea
Hippo Regius
Hadrumetum
Ad Maiores
0
200 km
0
150 miles



The Roman surveying instrument was the *groma*. It was used to lay out buildings, roads, aqueducts and ports.

The modern term *agronomy* is derived from this instrument.

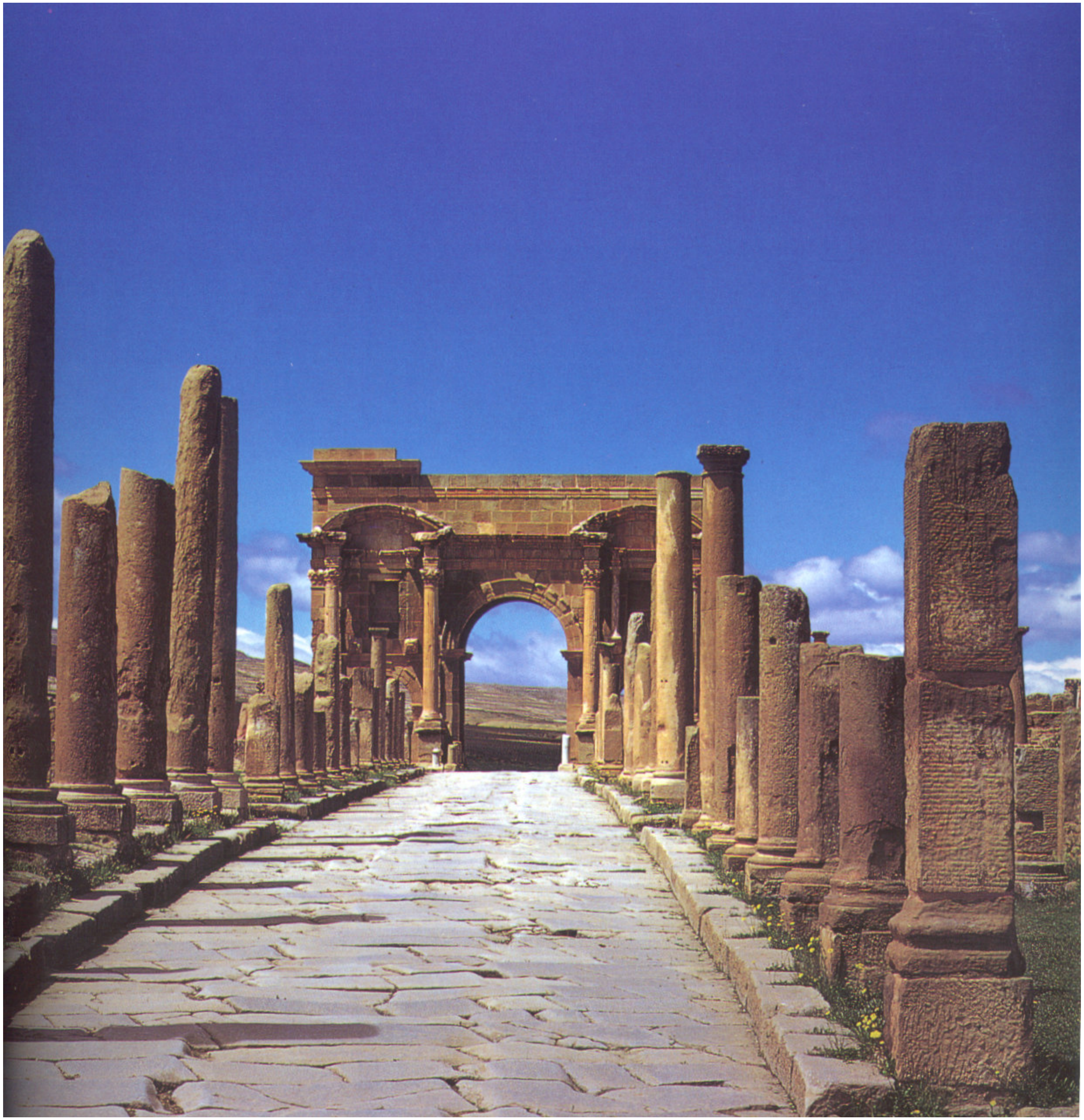
Using The Groma



Present day view of the *Via Aurelia*.

Traces of *Via Augusta* in downtown Córdoba.

Roman road into *Utica* (close to present day Tunis, North Africa).

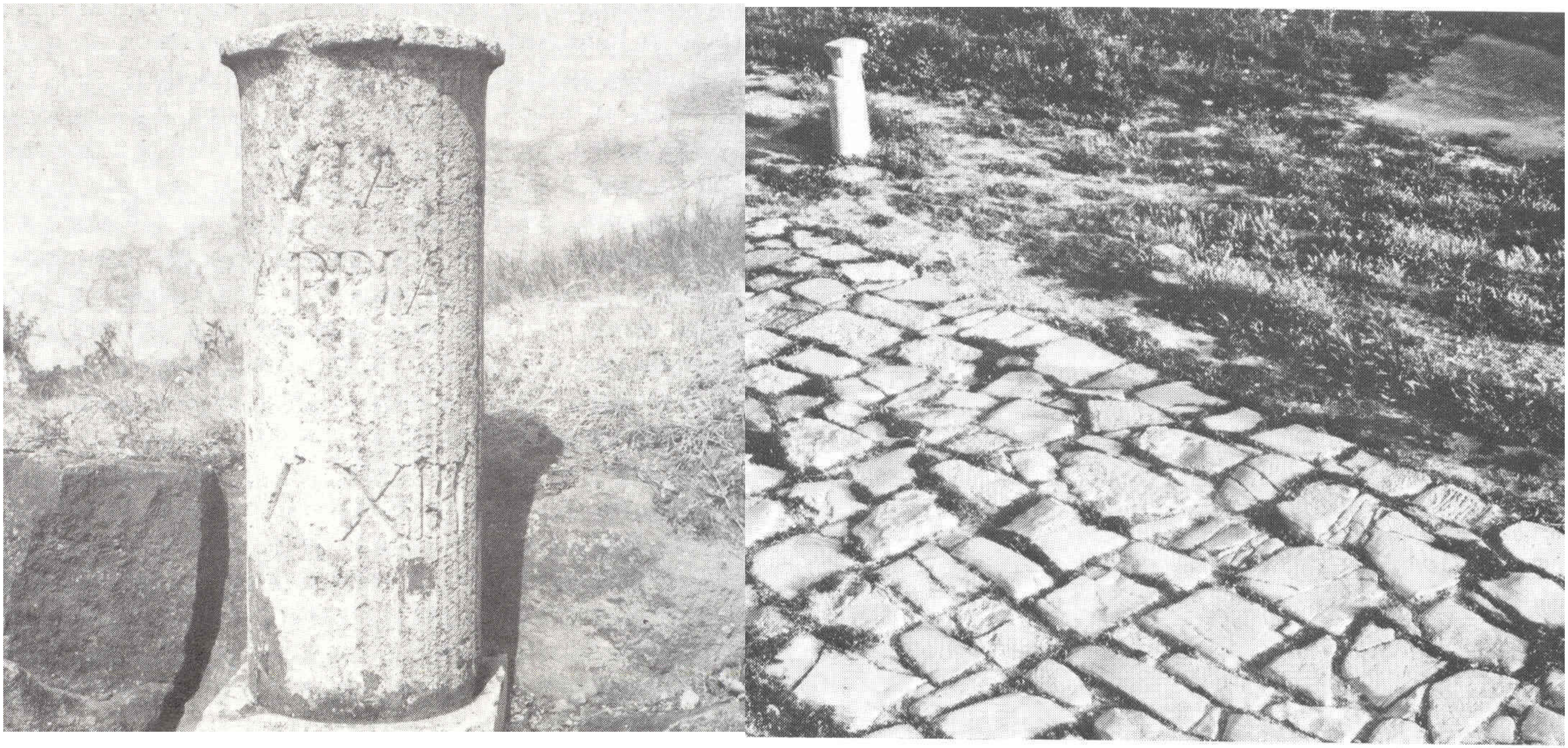


Timgad Street in
Ephesus, built in
32 AD.

A street of *Pompeii* as seen today. *Pompeii* was buried by Vesuvius in the year 79 AD.

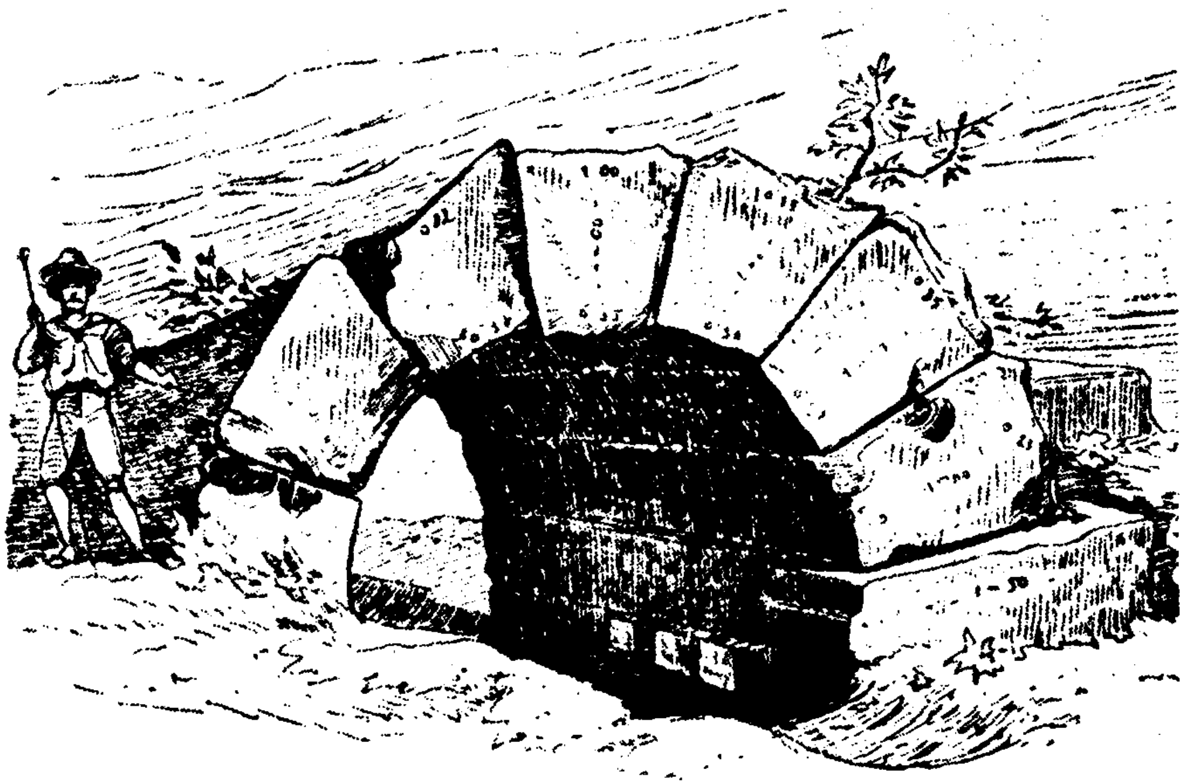
This photo shows a recently excavated milestone on the *Vía Appia* close to Rome.

The inscription reads as "*mile post 22*" (MP XXII) from the Rome of that time.

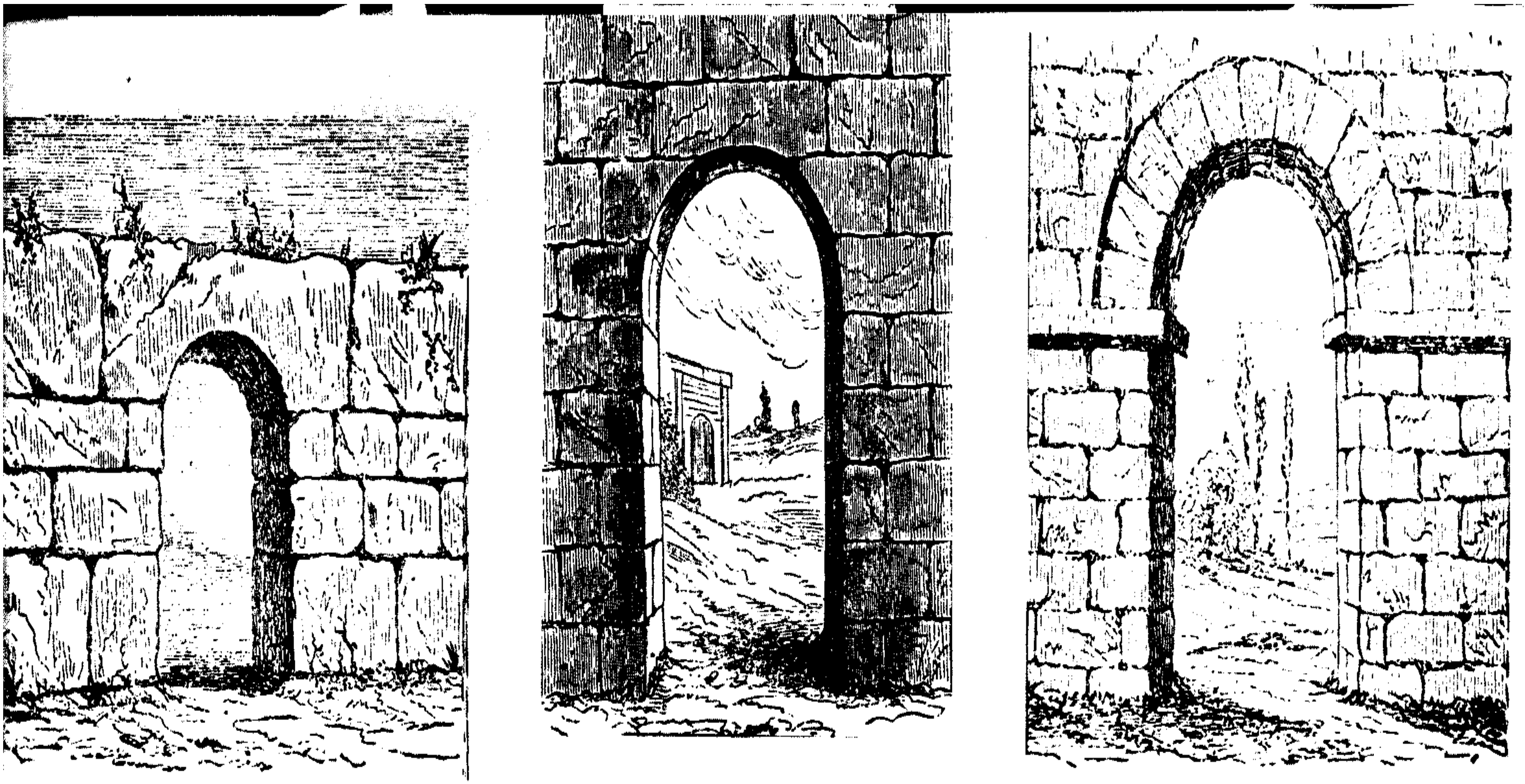


A Roman milestone at left, which stood by the *Via Appia*, 13 miles (19.2 km) from Rome. On the right, the Roman Carthage road, as it exists today.

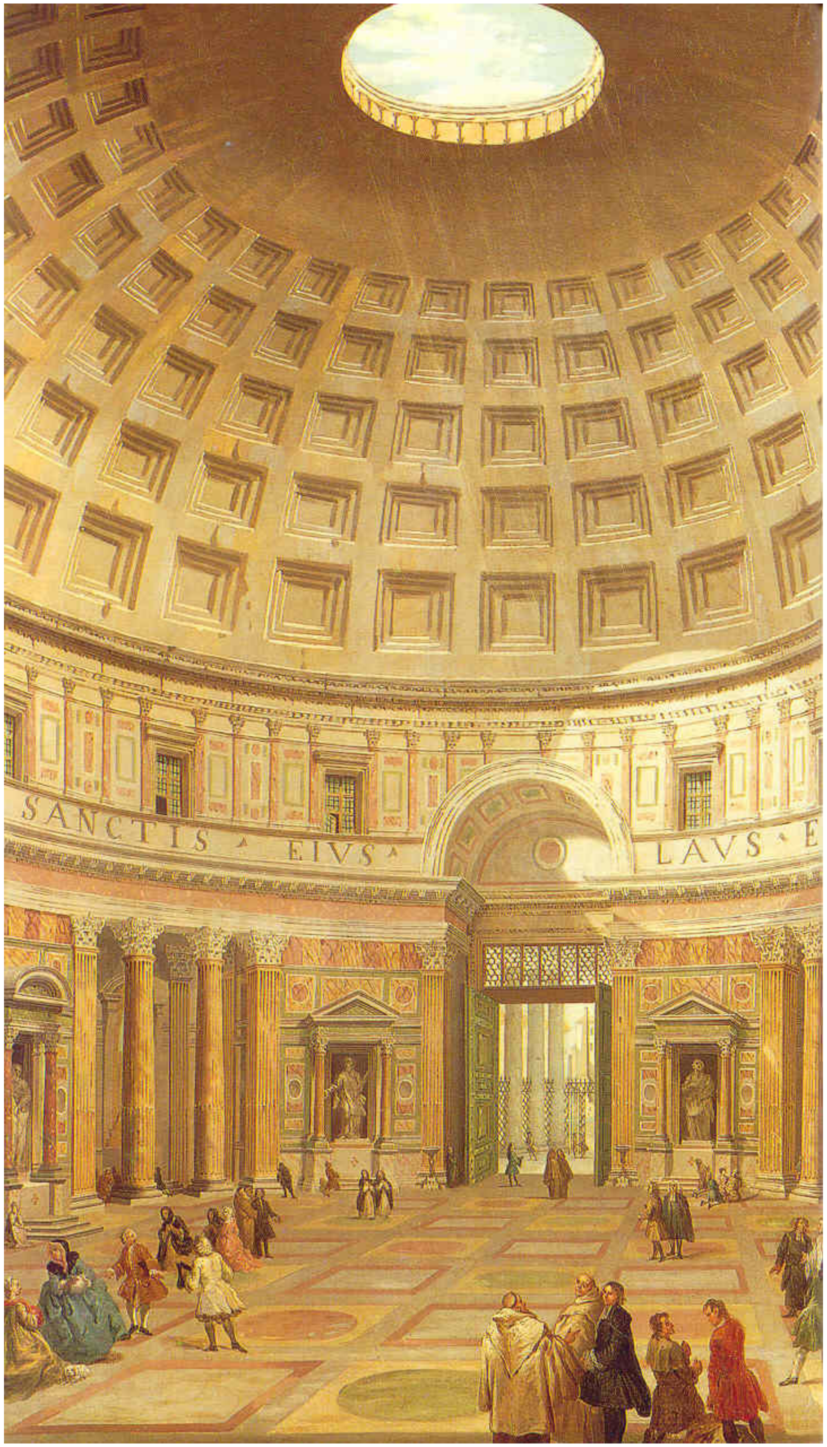
Arches, Vaults and Domes



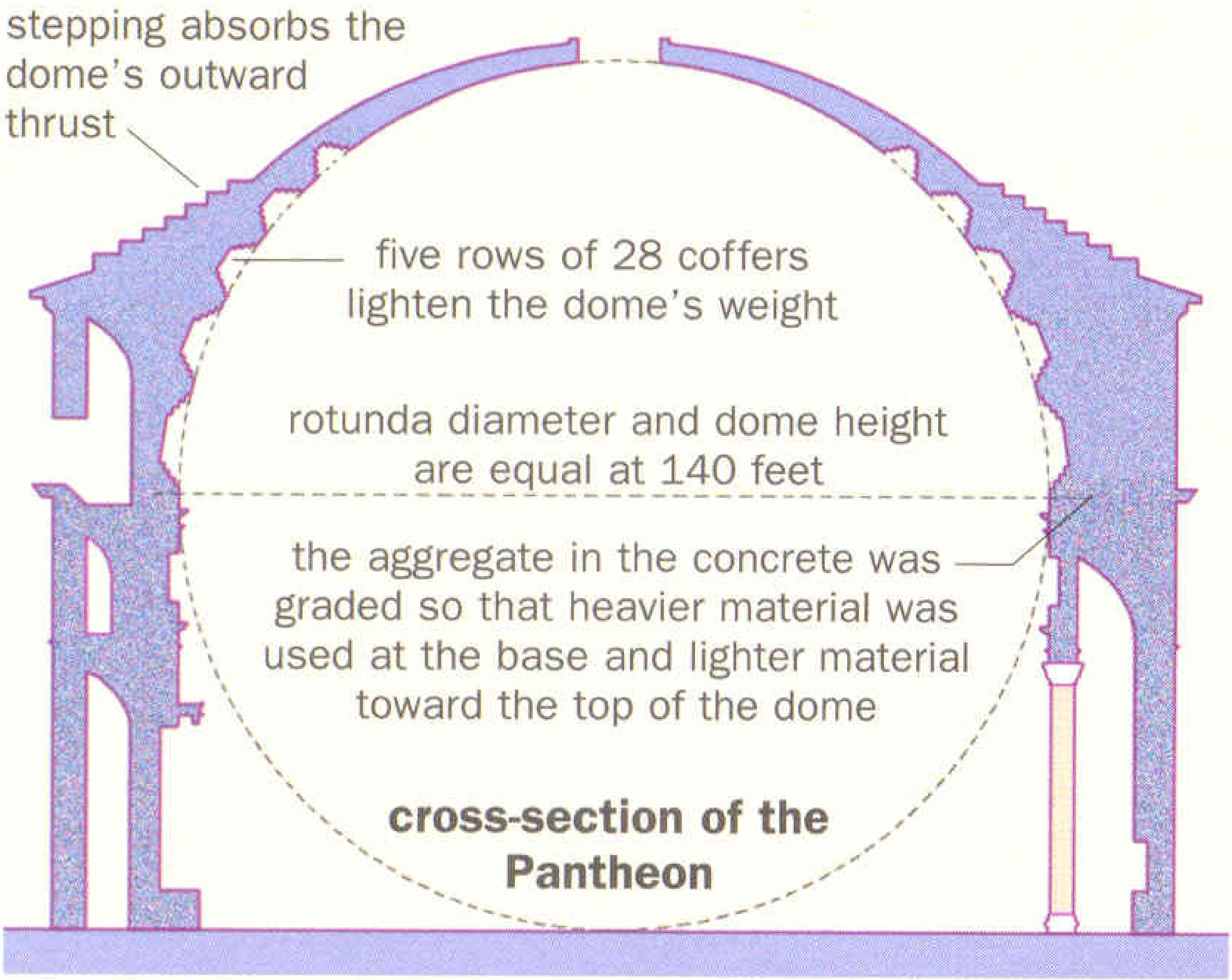
The first arch bridges were built by the *Etruscans* with timber. This figure shows the early Roman modification by first using masonry (circa 400 BC) and later, concrete cores with masonry shells.



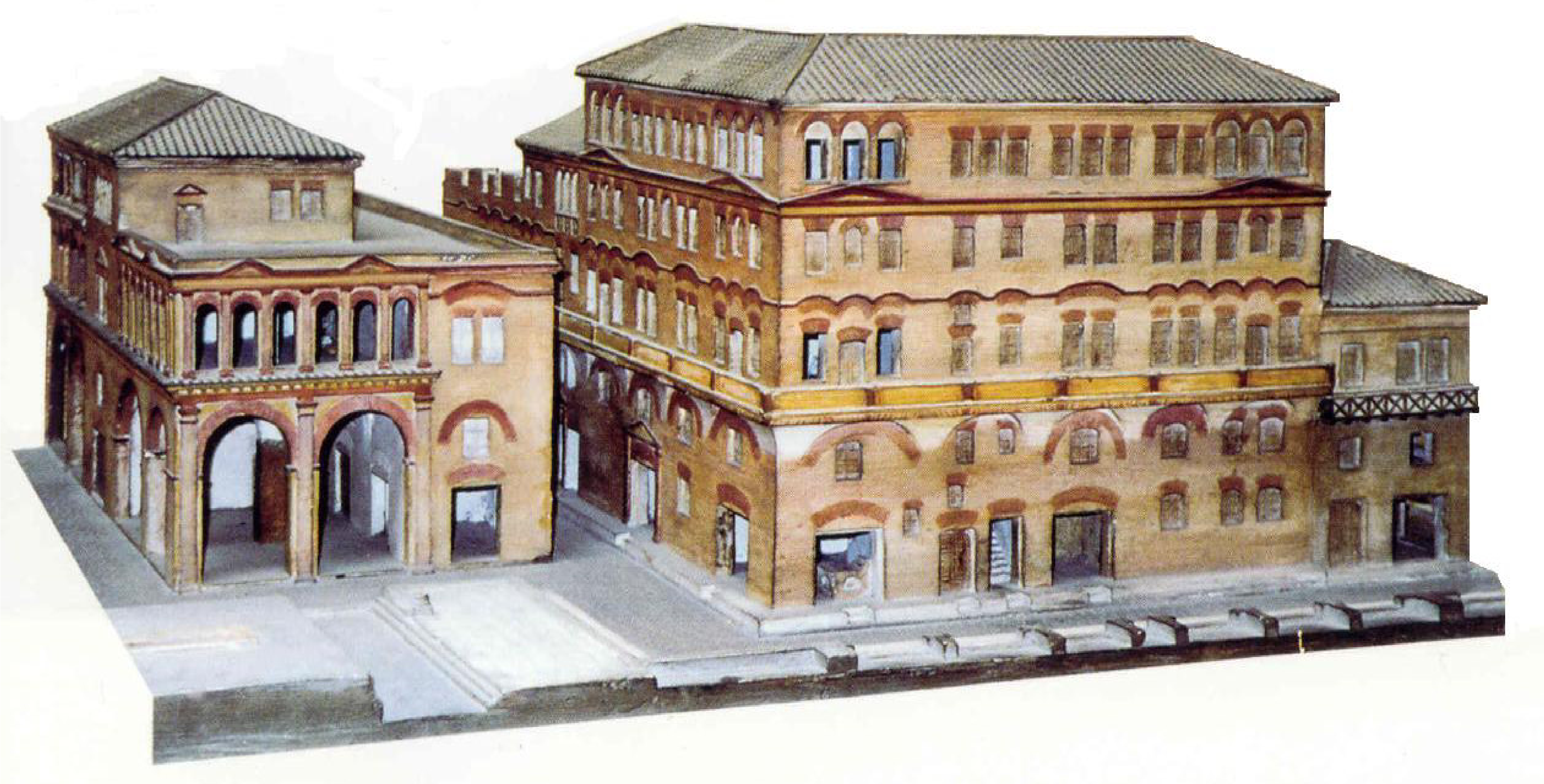
The early arches, previous to Etruscan and Roman arches, such as the arch in the left figure was not a true arch, but a shaped lintel (developed in Egypt). The middle figure shows a false arch, where all the forces are vertical. The figure on the right is a true arch, showing the stone *voussoirs* that follow the shape of the arch. The loads flow into the lateral piers.


SANCTIS EIVS LAVS


M AGRIPPA L F COS TERTIUM FECIT



cross-section of the Pantheon



Roman housing was also innovative and well-built. This model of 5-story houses by the River Tiber is based on excavations, which also discovered seven-story multi-family structures.

The Roman Forum at the time of emperor Trajan.

Bridges

Bridges.

In difficult terrain it was not possible for Roman engineers to construct long straight roads. They had to resort to embankments, bridges and even tunnels to achieve a reasonably direct route.

Bridges were constructed across rivers and depressions that were too deep for embankments. The earliest bridges were of wood. The oldest such bridge at Rome, and for several centuries the only bridge, may have been built by the Etruscans, although traditionally it has been attributed to King *Ancus Marcius*. This was called the *Pons Sublicius* ("bridge on wooden piles", from *pons* = bridge and *sublica* = timber pile), which was defended by *Horatius Cocle*s against the Etruscans in 508 BC. Afterward, it was rebuilt in wood in such a way that it could be dismantled easily in the face of attack. It was periodically swept away by floods and rebuilt.

Timber bridges were constructed by driving piles into the riverbed. The tips of the piles were sometimes protected by iron shoes. Transverse beams were fixed across the piles to form a trestle to support longitudinal timbers (today's "stringers" in steel or prestressed concrete girders) and the road decking. Although Roman timber bridges no longer survive intact, evidence for them has been found in excavations. They were frequently built in outlying provinces and for military use, whereas stone bridges became more common in the central provinces.

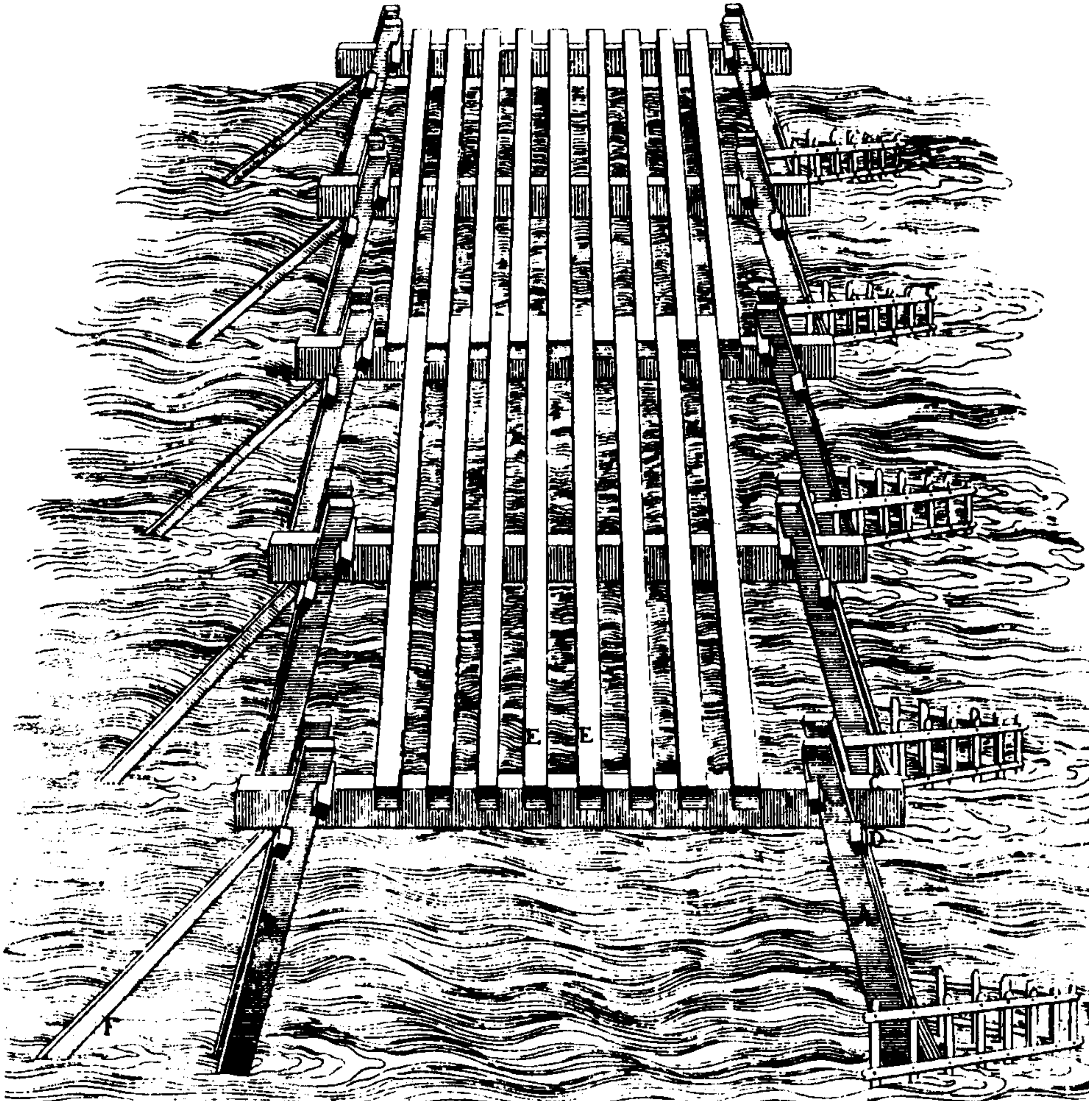
Scenes from Trajan's Column, showing legionaries crossing the Danube river on a pontoon bridge with timber walkways. The Roman river god *Danuvius* is depicted in the center.

Pontoon bridges were constructed of boats placed side by side. An example is shown in Figure 20 from ***Trajan's*** memorial column in Rome. Pontoon bridges could be assembled quickly and were especially useful in military operations. On a swiftly flowing river, the boats were secured by anchors and cables. This type of bridge required constant maintenance and was liable to damage by floating debris. They also prevented boat traffic on the river.

In S.A. Handford's 1951 translation of Julius Caesar's "***The Conquest of Gaul***", there is a description of one of Caesar's military bridges across the Rhine (Germany):

"For these reasons, Caesar determined to cross the Rhine. But a crossing by means of boats seemed to him both too risky and beneath his dignity as a Roman commander. Therefore, although construction of a bridge presented very great difficulties on account of the breadth, depth and swiftness of the river, he decided that he must either attempt it or give up the idea of a crossing.

The method he adopted in building the bridge was as follows. He took a pair of piles a foot and a half thick, slightly pointed at the lower ends and of a length adapted to the varying depth of the river, and fastened them together two feet apart. These he lowered into the river with appropriate tackle, placed them in position at right angles to the bank, and drove them home with pile drivers, not vertically as piles are generally fixed, but obliquely, inclined in the direction of the current. Opposite these, forty feet lower down the river, another pair of piles was planted, similarly fixed together, and inclined in the opposite direction to the current. The two pairs were then joined by a beam two feet wide, whose ends fitted exactly into the spaces between the two piles forming each pair. A series of these piles and transverse beams was carried right across the stream and connected by lengths of timber running in the direction of the bridge. Ten days after the collection of the timber had begun, the work was completed and the army crossed over".



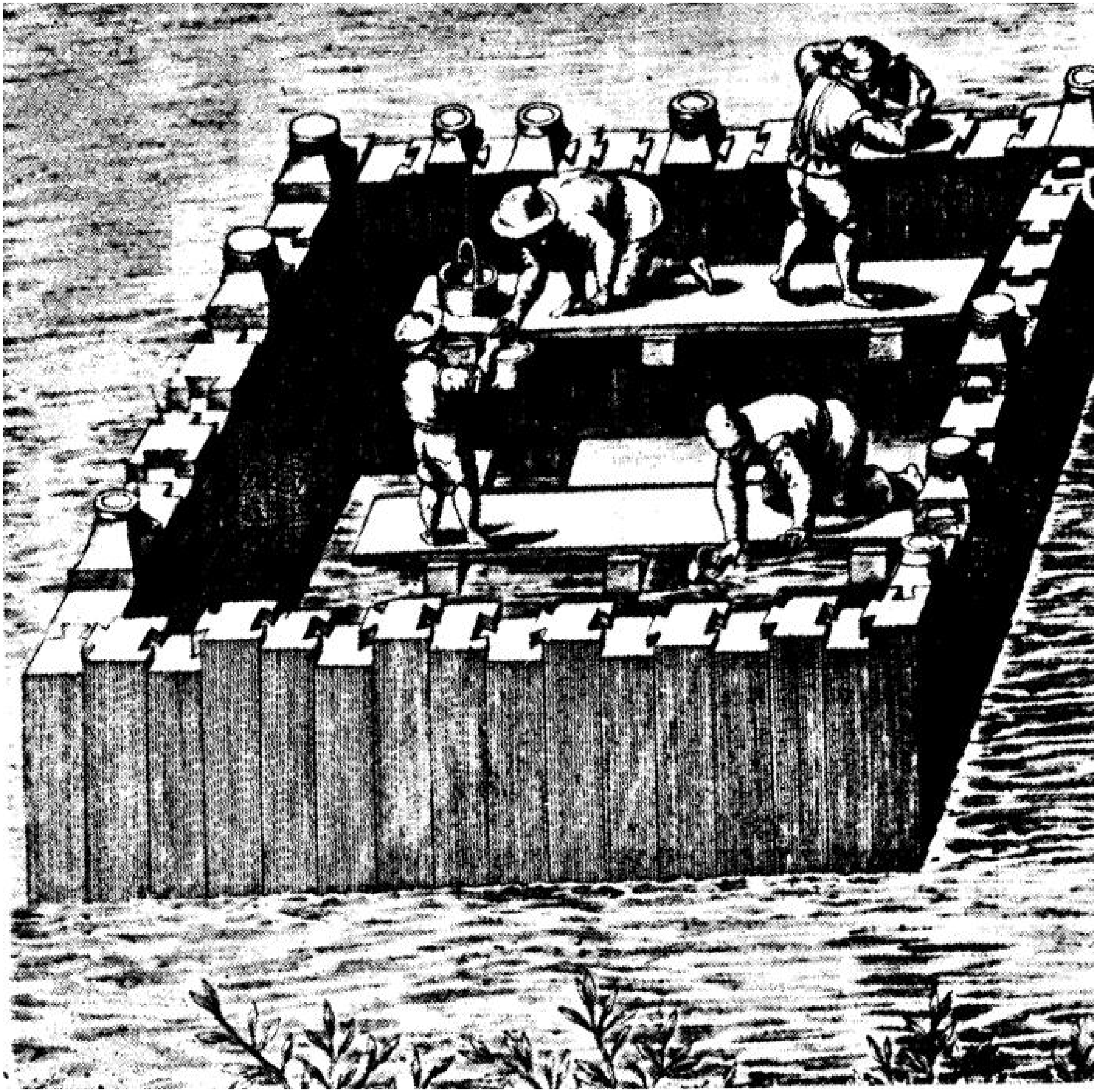
Julius Caesar's Rhine bridge as described by him in his book "*The Conquest of Gaul*".

The bridge is shown in the previous slide as envisioned by Palladio in his book of 1570 AD.

By the mid-3rd century BC, the weight-supporting arch was an important element of Roman construction and was soon adopted for stone bridges supported on piers. The earliest use came from Etruscan builders employed by the Romans. The importance of the arch was that it was under compressive forces all over. That is, its own weight, the roadway and the traffic pushed down on it, and produced no tensile forces. Therefore, it could be built of stone, brick or concrete, which are all materials poor in tensile but excellent in compressive forces. Since Romans were masters of masonry construction, they used arches for bridges, aqueducts, and even bathhouse arched vaults and the Coliseum's outer walls. Their maximum spans reached 100 feet and their shape was almost always that of a half-circle because of the ease of erecting wooden scaffolding of that shape.

The masonry arch was built of separate blocks or ***voussoirs***, which had to be temporarily supported on a wooden scaffolding structure. The arch was simultaneously started from both end piers, and when the top was reached, the final block (the "key-stone") was wedged between the two adjoining blocks. Once the keystone was in place, the scaffolding could be lowered, because each half-arch on each side leaned against each other. The piers that supported the arches could be constructed directly on the dry riverbeds during the summer in Mediterranean lands. In northern Europe, where rivers did not dry up, a cofferdam was first built. The most advanced type of Roman cofferdam was a double-layered box made of wooden planks, with the space between the inner and outer planks filled with clay. This box was floated into position and then weighted down until it sank. The water was then pumped out by an Archimedean screw (called a ***tympanum***).

A single arch Roman masonry bridge at Vaison-la-Romaine, Provence, France, is still carrying local traffic. Note the separate blocks or *voussoirs*.



This sketch shows the details of a Roman cofferdam using timber sheet-piling.

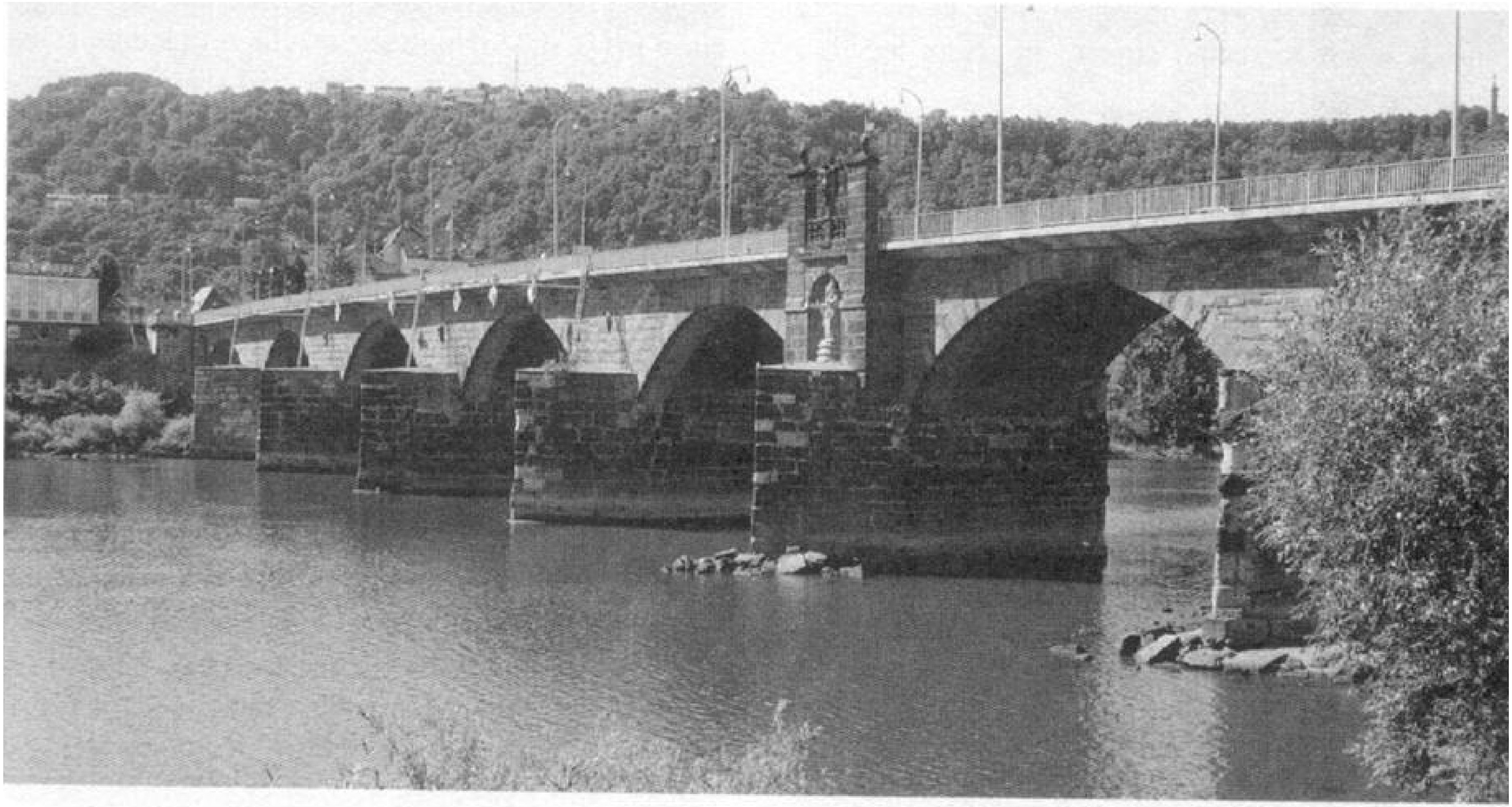
Note the sealing of the joints of the sheeting with clay (top right) to seal the cofferdam.

The water was removed from inside the cofferdam by means of a *tympanum*.

To prevent the bridge from sinking over time (settlement), the riverbed was first excavated to a firm foundation. Then, the base was filled with a hydraulic concrete to form the pier's foundation. Where there was no firm foundation (for example, when faced with deep strata of silt or clay) piles were driven into the riverbed using a crane. The upper piles could be used as a superstructure for a trestle, which supported a wooden roadway. Alternatively, the piles were cut short at the riverbed level, capped with masonry, and the piers were built on top of them with masonry and concrete.

Construction techniques for aqueducts and for bridges over rivers were similar. Masonry blocks were used originally for both. However, from about 100 AD, pozzolanic cement (from volcanic ash) became popular. The core of the piers were made from concrete using the new cement, and then faced with rock masonry or brick. This type of construction was known as ***opus incertum***.

Piers tended to obstruct the flow of a river, therefore, Roman engineers overcome this problem by constructing triangular cut-waters on the upstream end. An example of this is shown in Figure 26, of the Roman bridge at Trier, Germany, over the Moselle River. The cut-waters protected the pier foundations by diverting the water (and ice in winter) around the sides. Bridges over tidal rivers would have cut-waters on both the upstream and downstream ends of the pier foundations. Another example is the Roman bridge at Córdoba, Spain, over the Guadalquivir.



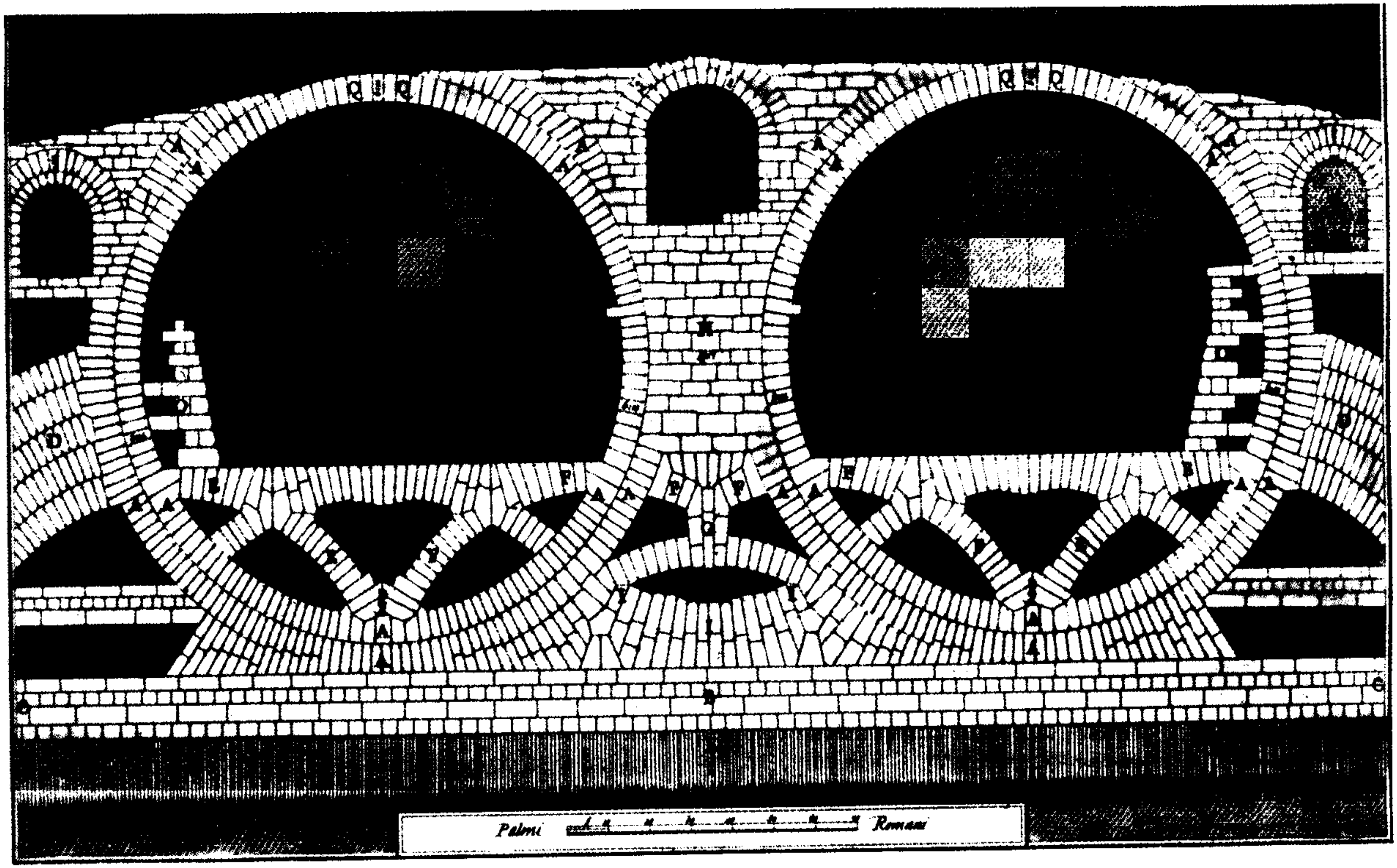
The Roman bridge over the Moselle River at Trier, Germany shows the triangular cutwaters at each pier to protect against ice. The piers are Roman, but the superstructure is modern.

The bridge roadway was carried on arches that sprang from the piers and were either timber in the earlier bridges (prior to 350 BC) or masonry. Arches were almost all semicircular in shape, since Roman engineers could not build flattened (that is, segmental) arches of great width. In order to minimize the number of piers, the height of the central arch was increased, so that its width could also be increased. The arches on either side of the central arch were made progressively lower, which would give a humpback to the road surface at the center of the bridge. A clear example of this technique is the *Pons Fabricium* in Rome. Many bridges had only a single arch, such as the one of Provence, France. Bridges on navigable rivers had to have sufficient headroom for boats to pass underneath.

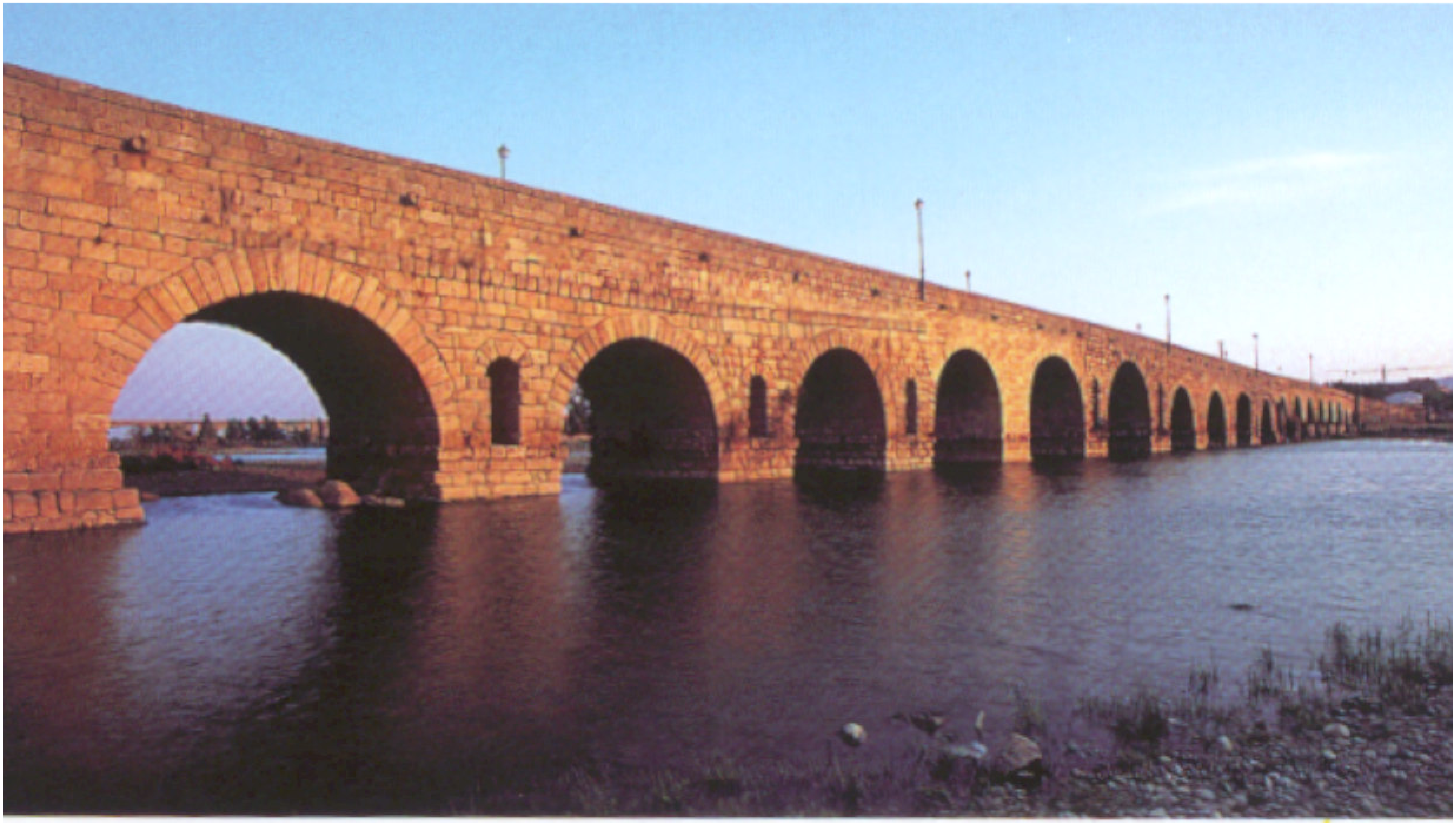
Many surviving bridges have drainage apertures in the masonry between the arches, so that the structure was not weakened when floodwaters rose above the spring of the arches, as shown in the Guadiana Bridge.

Roman cities such as Rome, London and Bordeaux were often sited at the lowest bridging point of rivers. At least 12 bridges existed at Rome, and hundreds more are known from the rest of the Roman world, including ones built during military operations. Because the bridges were so well built, they often can withstand modern traffic. Many are still in use, while others were replaced only in the 18th century when increased control of rivers led to a change in water flow. In addition to bridges across rivers, there were also ferries, and river fords that were used, particularly for secondary roads.

The Roman bridge at Córdoba crosses the Guadalquivir ("*great river*" in Arabic) was part of the ***Via Augusta*** that extended 2500 km from Narbona (France) to Cádiz (Spain) on the Atlantic.



Reconstructed section of the masonry bridge foundations for the ***Pons Fabricium*** in Rome.



The Guadiana River bridge in Spain is the longest surviving Roman bridge with 60 arches, and a total length of 800 meters.

Aqueducts

Aqueducts.

Although in some instances water was obtained from nearby springs and rivers, in most towns the supply came largely from wells. Towns such as London never had an aqueduct but relied on wells, which were usually circular or square shafts dug to intercept the local water table. They were lined with stone or with wood, and in some instances wooden barrels with the ends removed were used for a lining. Stone-built cisterns, some extremely large, were also used in towns to store water, particularly in the eastern empire.

Some towns were supplied with water from a nearby source through an aqueduct. In most if not all cases, the initial reason for constructing an aqueduct was to supply a large quantity of water for use in the public baths. Once such a supply was established, it came to be used for drinking water and for private bathhouses as well.

Wherever possible, aqueducts ran at ground level or were buried just below it, in channels or in pipes. The water usually ran in a covered conduit built of stone and lined with waterproof cement. The conduit was normally only half full of water; the extra height was used to enable removal of calcium carbonate deposits that formed inside the conduit and so narrowed the water channel. There were inspection chambers at ground level for access. In a few instances it was necessary to carry the channel of the aqueduct across a valley using a bridge, usually built on a series of arches such as shown in Figure 31 for the ***Pont du Gard*** at ***Nîmes*** in France.

An aqueduct was built with a downhill gradient from the source to the town, so that water flowed to the town under gravity. In low-lying terrain, the aqueduct was carried on long masonry arcades in order to maintain the gradient. The ruins of these bridges across valleys and of arcades of arches across low-lying land are most easily recognized as the remains of aqueducts.

While pumps are known to have been used in Roman times (such as the ***tympanum***), they were hardly used aqueducts. Where it was not possible to build a bridge to carry an aqueduct channel across a valley, the water was diverted into a series of closed pipes (usually of lead or ceramic). The pipes passed down one slope of the valley and up to a lower point on the other side where the aqueduct became a channel once more. Using the inverted siphon principle, the water flowed through the pipes until it found its own level again. A bridge could be built across the bottom of the valley to take the pipes, and such bridges resemble ordinary aqueduct bridges or arcades. Pipes must have been difficult to clean and were probably more expensive to install than building aqueduct bridges with channels.

Because the water flowed under gravity, an aqueduct was routed to the highest part of a town. The water was passed through one or more settling tanks to a distribution tank (***castellum, castellum aqua*** or ***castellum divisorum***), from where supplies were distributed to other districts using conduits or pipes. The one at ***Nîmes***, France shown in Figure 31, distributed the water through 13 large lead pipes that supplied various parts of the town. For distribution at a local level, pipes of lead, ceramic, leather and wood were used.

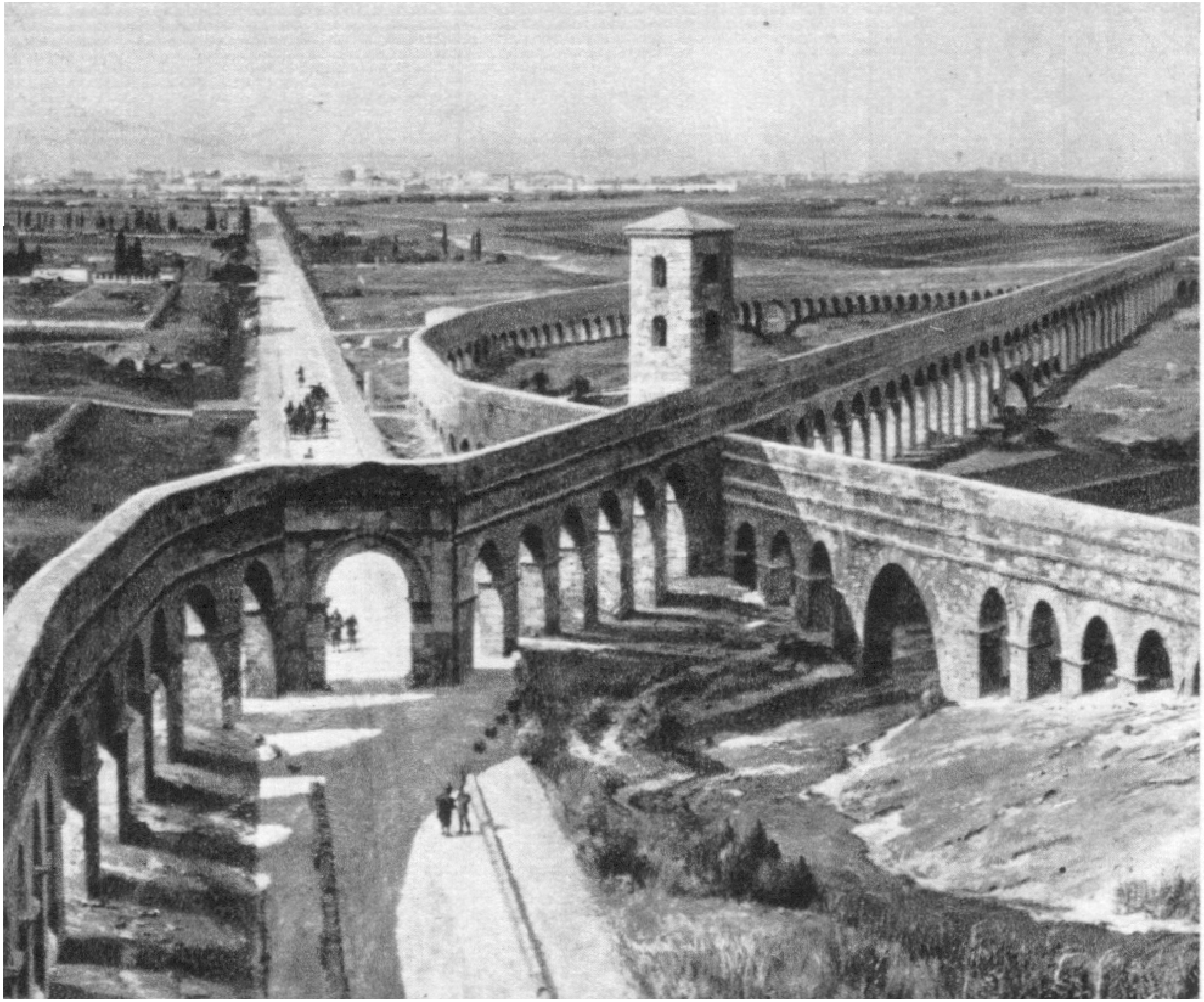
Householders had to pay for a water supply based on pipe diameter, the standard measuring unit being the ***calix*** = nozzle (plural = ***calices***). Details of the aqueducts supplying Rome are given in the book "***On the Water Supply of Rome***", written in the late 1st century AD by ***Frontinus***, who was in charge of Rome's water supply at that time. It has been estimated that Rome was supplied with around half a million to 1 million cubic meters daily.

The oldest aqueduct supplying the city of Rome was the ***Apio*** built in 312 BC with buried pipes. The first arched aqueduct was the ***Anio Vetus***, in 272 BC. The ***Aqua Marcia*** shown in Figure 33 was originally 90 km long when built in 144 BC. Later it was augmented in length, and by 35 BC it was connected with another aqueduct ***Aqua Julia*** with three separate levels of operations.

Many Roman aqueducts have survived twenty centuries of use, and can be seen today at Acqui, Tarragona and Segovia in Spain, at Nîmes, Lyón, Paris and Marseilles in France.

Aqueducts delivered a continuous supply of water that could not be stopped, only diverted, so that provision of such a water supply also required provision of a drainage system.

Underground sewers, usually built beneath the streets, carried overflow water and waste from latrines and bathhouses. Sewers were usually built of stone, sometimes of timber, and the main sewers of a town could be of a considerable size. They were equipped with manholes at regular intervals that provided access for cleaning and repair by the municipal slaves.



The Roman aqueduct of ***Aqua Marcia***, built in 144 BC was originally 90 km long. In 35 BC, it was connected to the aqueduct of ***Aqua Julia*** on three levels. Rome is in background.

The remains of the aqueduct *Aqua Anno Novus* which was able to deliver up to 189,000 m^3 of water every day to the city of Rome.

The largest Roman aqueduct was at Segovia, Spain.

Built with granite blocks without mortar, it is 800 m long and 30 m high.

It was built in 41 AD and stills supplies water to Segovia.

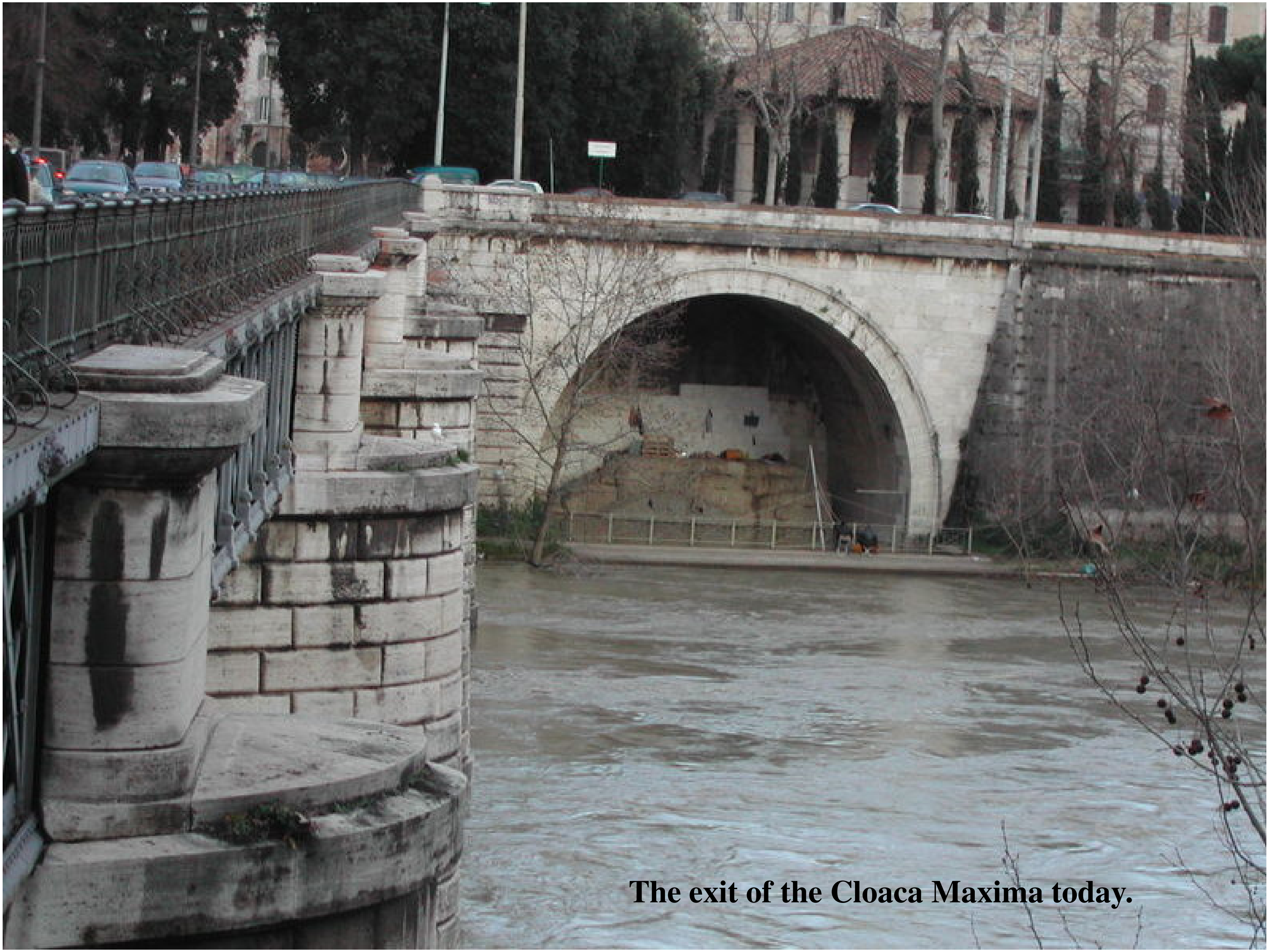
The Roman ***Pont du Gard*** aqueduct is 49.4 m high over the Gardon River in ***Nîmes***, France. It was finished in 18 BC and carried water 50 km to the Roman city of ***Nemausus*** (Nimes).

Smaller drains consisted of covered stone or timber-lined channels, or were built of tiles mortared together to form a vault. In some towns water was supplied to public drinking fountains in the streets, which fed stone tanks, the overflow from which drained into the sewers. Channels or gutters in the streets carried away surface water and may sometimes have acted as open sewers. The effluent from drains and sewers was discharged into cesspools, called ***cloaca***, or soak-ways or more often, into nearby rivers.

Rome consumed 300 million gallons of water every day. In order to get rid of these 300 million gallons/day the Romans used an underground sewer system.

The system was first constructed to drain the marshlands that the City of Rome was built upon. They called it the Cloaca Maxima (translation: Greatest Sewer).

Although no longer used to transport sewage, the Cloaca Maxima is still used today to deal with storm water. In the very beginning a portion of the Cloaca Maxima needed to be tunneled through the surrounding hills in order to drain the swamps.



The exit of the Cloaca Maxima today.

Road Tunnels and Mining

Tunnels.

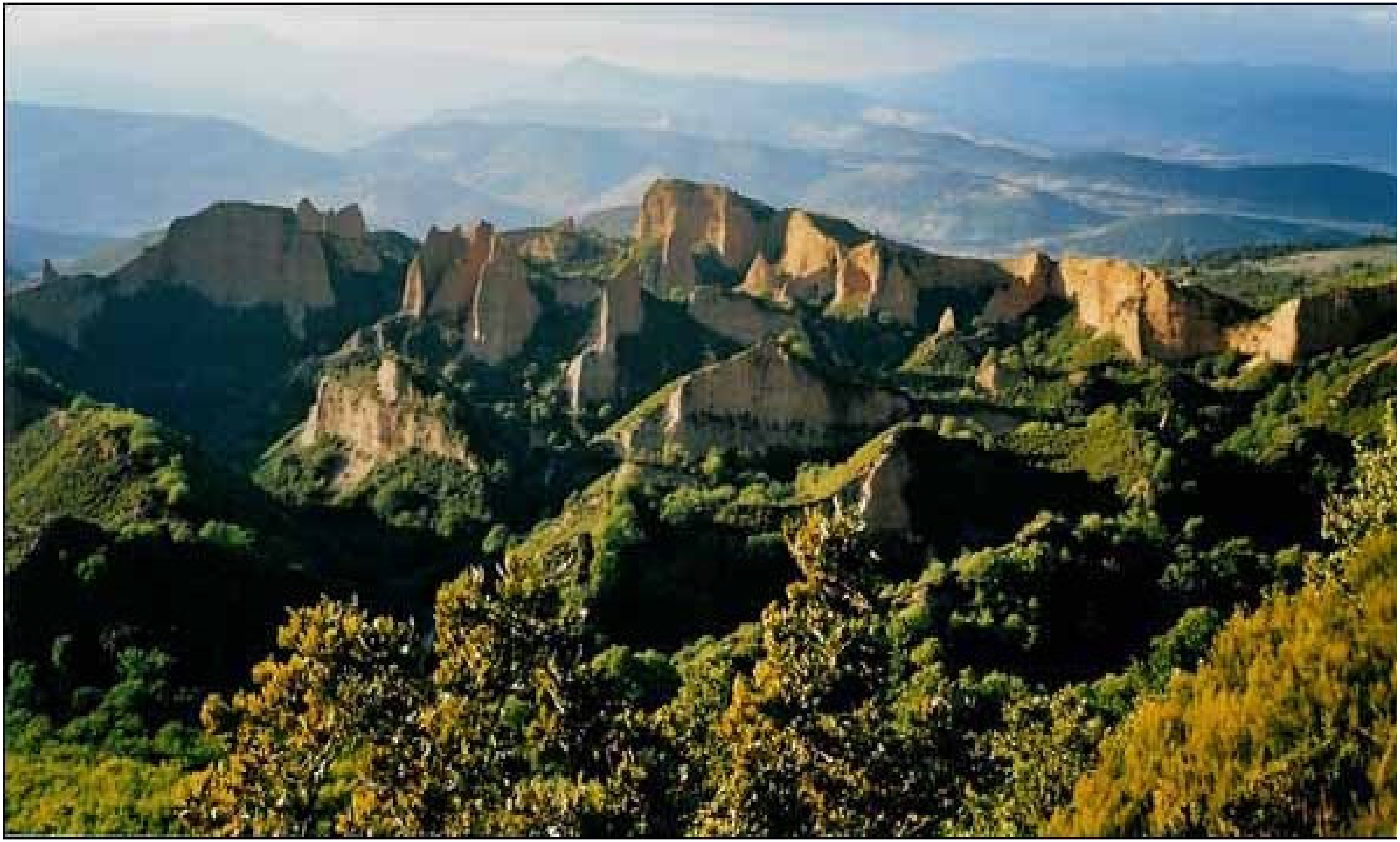
The Romans built a large number of tunnels, mostly for mining, but some also for roads, although they were used only for major highways which would otherwise have a long diversion.

The best examples of tunnels still in use today include the *Furio* tunnel, which was cut through a solid limestone formation at the Furio Gorge on the *Via Flaminia* near present-day Pesaro. Emperor *Vespasian* had it excavated in 76 to 77 AD. It was 5.48 m (18 ft) wide, 5.95 m (19 ft 6 in) high and 38.3 m (125 ft 7 in) long and is still in use today. It replaced another shorter older tunnel which had been dug originally by the *Umbrians*.

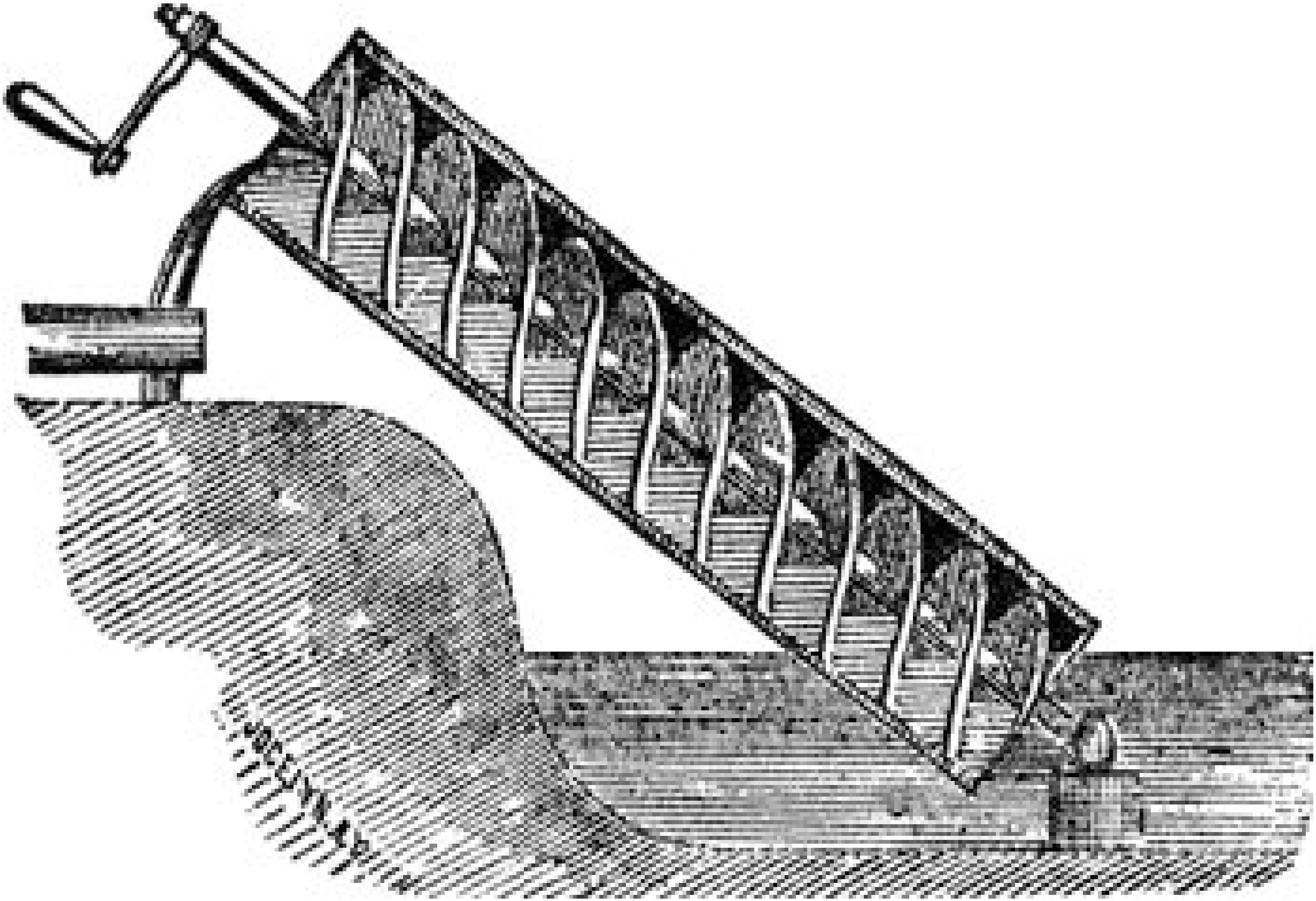
The road tunnel between *Pozzuoli* and *Naples* (the *Crypta Neapolitana*) on the *Via Domitiana* was 705 m (2,313 feet) long, about 4 m (13 feet) wide and 5 m (16 ft 5 in) high and was lit with oil lamps. It was famous for being notoriously dusty and even so remained in use until recently.

Roman tunnel from Ponza village to Chiaia di Luna.

Britain's gold mines were located in Wales at Dolaucothi. The Romans discovered the Dolaucothi vein soon after their invasion, and they used hydraulic mining methods to prospect the hillsides before discovering rich veins of gold-bearing quartzite. The remains of the several aqueducts and water tanks above the mine are still visible today. The tanks were used to hold water for hushing during prospecting for veins, and it involved releasing a wave of water to scour the ground and remove overburden, and expose the bedrock. If a vein was found, then it would be attacked using fire-setting, a method which involved building a fire against the rock. When the hot rock was quenched with water, it could be broken up easily, and the barren debris swept away using another wave of water. The technique produced numerous opencasts which are still visible in the hills above Pumsaint today. A fort, settlement and bath-house were set up nearby in the Cothi Valley. The methods were probably used elsewhere for lead and tin mining, and indeed, were used widely before explosives made them redundant. Hydraulic mining is however, still used for the extraction of alluvial tin.



At alluvial mines, they applied their *hydraulic mining* methods on a vast scale, such as Las Medulas in north-west Spain. Traces of tanks and aqueducts can be found at many other early Roman mines. The methods are described in great detail by Pliny the Elder in his *Naturalis Historia*. He also described deep mining underground, and mentions the need to dewater the workings using *reverse overshot* water-wheels, and actual examples have been found in many Roman mines exposed during later mining attempts. The copper mines at Rio Tinto were one source of such artifacts, where a set of 16 was found in the 1920s. They also used *Archimedean screws* to remove water in a similar way.



The Archimedes Screw was the primary method used by the Romans to remove water from their mines.

Roman masonry

Recent steel reinforcement

Sintered archaic masonry

Highly compressed section

Fig.10: From the north entrance into the Eupalinos tunnel. (left to right)