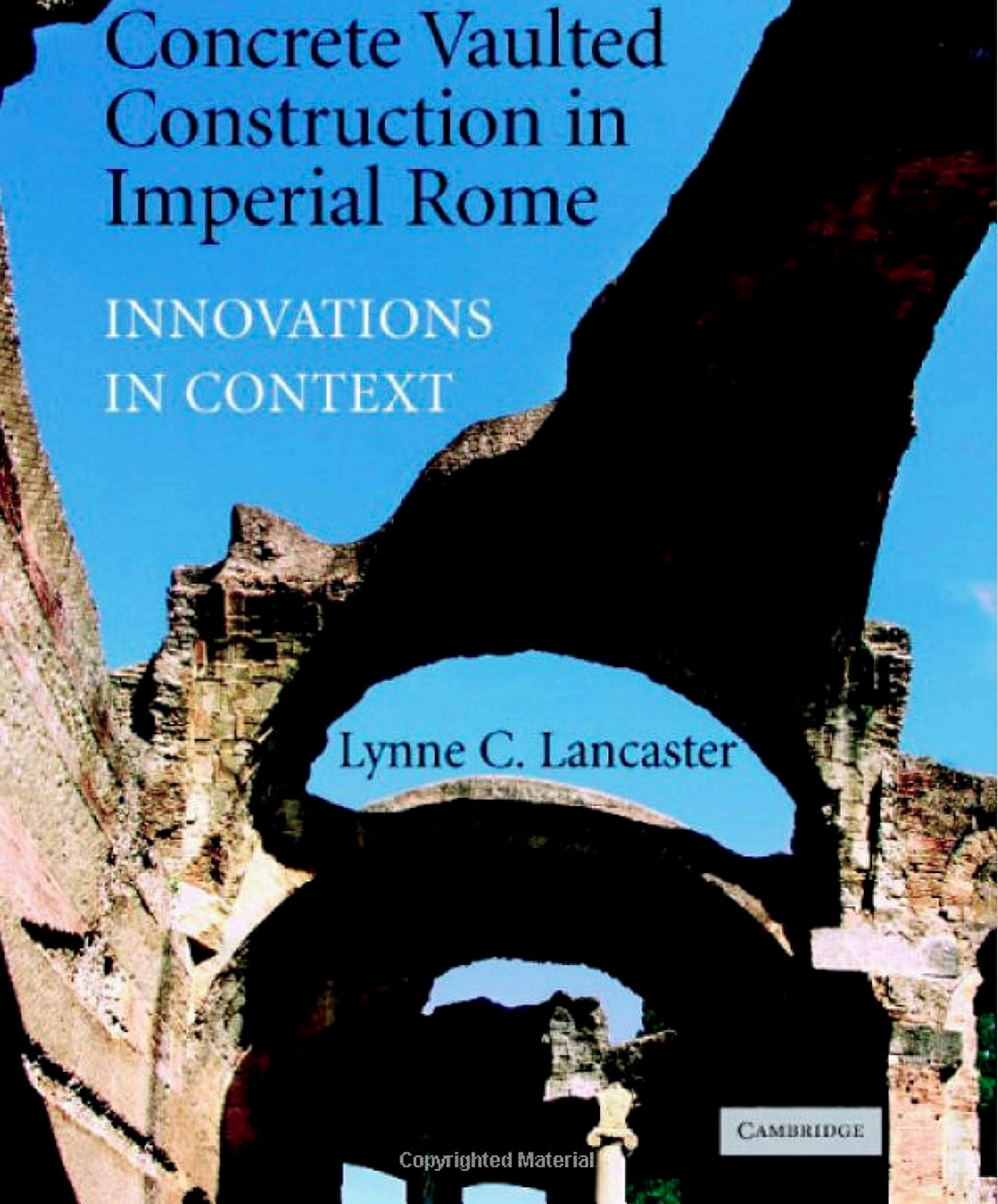
Concrete Vaulted Construction in Imperial Rome

INNOVATIONS IN CONTEXT



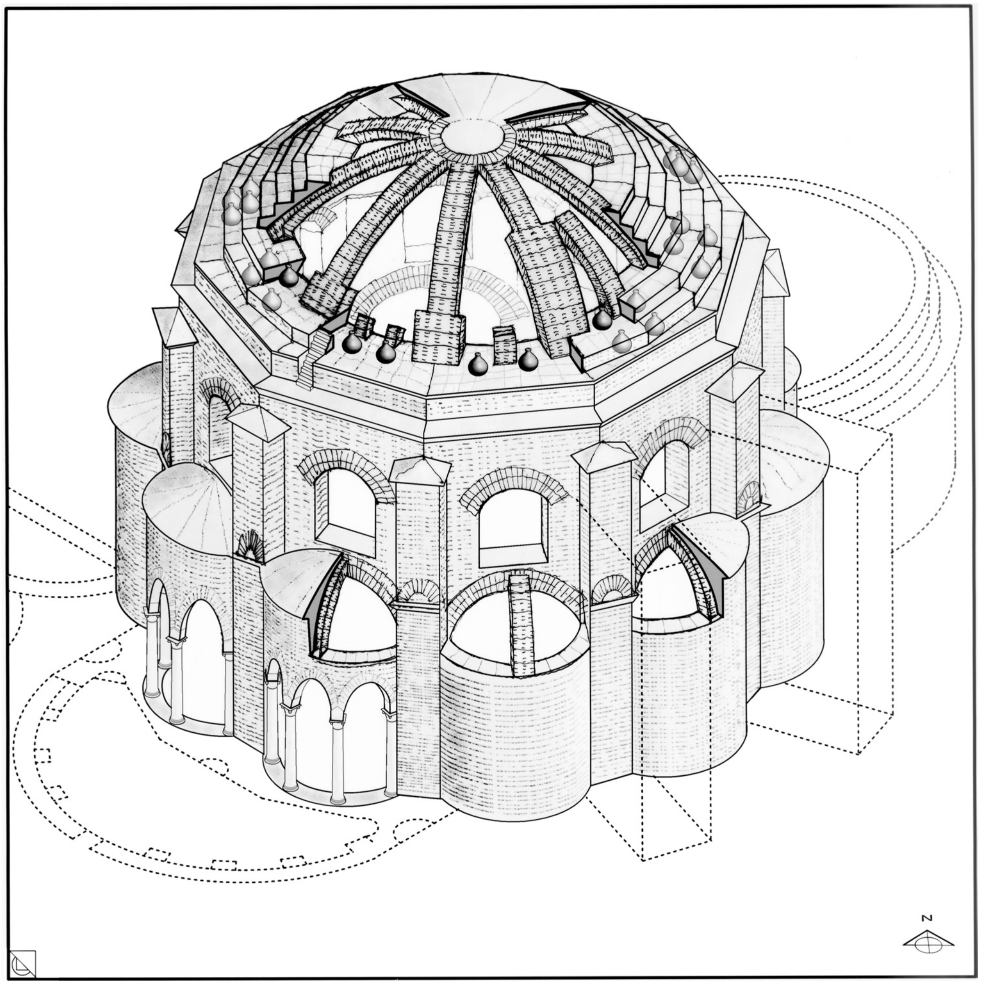
Lynne C. Lancaster

CAMBRIDGE

CONCRETE VAULTED CONSTRUCTION IN IMPERIAL ROME

Concrete Vaulted Construction in Imperial Rome examines the methods and techniques that enabled builders to construct some of the most imposing monuments of ancient Rome. Focusing on structurally innovative vaulting and the factors that influenced its advancement, Lynne Lancaster also explores a range of related practices, including lightweight pumice as aggregate, amphoras in vaults, vaulting ribs, metal tie bars, and various techniques of buttressing. She provides the geological background of the local building stones and applies mineralogical analysis to determine material provenance, which in turn relates to trading patterns and land use. Lancaster also examines construction techniques in relation to the social, economic, and political contexts of Rome, in an effort to draw connections between changes in the building industry and the events that shaped Roman society from the early empire to late antiquity.

Lynne Lancaster is assistant professor of classics at Ohio University. An architect and archaeologist, she is a Fellow of the American Academy in Rome and has published in a variety of journals, including *American Journal of Archaeology*, *Journal of Roman Archaeology*, and *Römische Mitteilungen*.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INNOVATIONS IN CONTEXT

LYNNE C. LANCASTER
Ohio University

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For Tom

I believe that in architecture, as in all art, the artist instinctively keeps the marks which reveal how a thing was done.

– Louis I. Kahn

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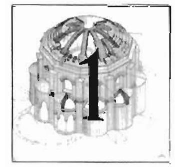


INTRODUCTION

Concrete vaulted structures represent one of the ancient Romans' most original and enduring contributions to the artistic and architectural patrimony of the Mediterranean world. A combination of factors led to the development of the large spans and curvilinear forms still visible in buildings such as the Pantheon and the Basilica of Maxentius. Rome was endowed with a wealth of natural resources in its immediate environs, and what it could not supply for itself it could bring in from afar through the development of extensive trade networks. Along with the financial benefits of conquest came the architectural, technological, and mathematical expertise of the architects, builders, and engineers from the conquered territories. Augustus, in bringing the civil wars to an end, also brought a vision of urban renewal for Rome that provided incentive for more grandiose schemes than had previously been possible. By that time, the architects and builders had over a century of collective experience with concrete construction, but Augustus's creation of an organizational infrastructure provided a context in which new ideas and larger building schemes were possible. As emphasized by W. L. MacDonald, the fire that devastated much of Rome during Nero's reign in A.D. 64 effectively cleared the slate and provided opportunities to exploit the fireproof nature of concrete and in doing so created a new aesthetic based on the plastic potential inherent in the material.[1] In imperial Rome, all of the natural advantages and cultural influences came together and manifested themselves in imposing concrete vaulted structures, the remains of which are the focus of this study.

My intention is to examine the changes that occurred in the choice of materials and techniques used in concrete vaulted construction in Rome from the time of Augustus to Constantine and to place the results in the wider social, economic, and political context. I document the appearances of particular materials and building techniques and examine the reasons for their use and the ways that use changed over time. In particular, I am interested in techniques that aided in the creation of large and complex structures, such as the use of lightweight concrete, brick vaulting ribs, metal tie bars, and various forms of buttressing. In some cases, the choices of the builders were affected by external factors such as the availability and the cost of materials or the changes in the infrastructure of the building industry itself. The interplay between the decisions made on the building site and these external factors can create a window into the complexities of urban and suburban life in Rome.

A NOTE ON MONUMENTS AND PREVIOUS SCHOLARSHIP

The monuments included in this study date from the reign of Augustus (27 B.C.), when the resources of the Mediterranean basin became widely available in Rome, to the reign of Constantine, when patronage was diverted to the new capital inaugurated at Constantinople (A.D. 330). The monuments are for the most part limited to buildings in the city of Rome and its immediate environs because I am particularly concerned with the local materials and the economic, social, and political factors unique to the capital city. Many of them are state-sponsored public monuments, such as the imperial thermae, basilicas, and places of public spectacles like theaters and amphitheaters. Some are imperial residential structures such as the palaces on the Palatine, the domed pavilion in the Horti Sallustiani, or the nymphaeum in the Horti Liciniani ("Temple of Minerva Medica"). Some structures in the immediate outskirts of Rome also are included, such as the Villa alla Vignaccia, the Villa di Sette Bassi, and the so-called Villa of the Gordians. Further afield are two imperial villas, Domitian's Villa in the Alban hills and Hadrian's Villa near Tivoli, both of which demonstrated innovative vaulting techniques that relate to developments in Rome itself. During the early fourth century, domed mausolea often located on suburban villas became popular, and these extramural structures are also examined. One monument important to this study is located outside of the immediate environs of Rome. The structure, known as the "Temple of Mercury" at Baiae on the Bay of Naples, is both the earliest preserved concrete dome and the largest spanned dome before the Pantheon and hence must be considered in any discussion of the development of concrete vaults.

One goal of the present work is to provide a synthetic study of the concrete vaulting in Rome by combining my own on-site observations with those of others to create an overview of the developments. This would not be possible without the publication of monographs during the past few decades by scholars conducting fieldwork on some of the major monuments in Rome: K. de Fine Licht on the Pantheon (1968), the Baths of Trajan (1974), and Sette Sale (1990); C. M. Amici on the Forum of Trajan (1982) and the Forum of Caesar (1991); J. E. Packer on the Forum of Trajan (1997); J. DeLaine on the Baths of Caracalla (1997); and J. J. Rasch on a series of late Roman domed structures including the Tor de'Schiavi (1993) and the Mausoleum of Helena (1998). The engineering works of J. Heyman (1995, 1996) and R. Mark (1982, 1990) have been particularly influential in my approach to the structural aspects of vaulting. I also have drawn on numerous articles by archaeologists, geologists, and engineer/architects working in Rome as well as on the invaluable resource of E. M. Steinby's *Lexicon Topographicum urbis Romae* (1993–2000). Although the study is in the spirit of previous works on Roman construction such as those by M. E. Blake (1947, 1959, 1973), G. Lugli (1957), J.-P. Adam (1994), and C. F. Giuliani (1990), my focus is narrower and my inquiry delves deeper into specific issues relating to the construction of large-scale concrete vaulting.

HOW TO USE THIS BOOK

The book is organized so that it can be used by both general readers and specialists. The material in the remaining sections of this chapter and in the final chapter ("Innovations in Context") is intended to provide general discussions accessible to a wide audience. Each of the other chapters is provided with a brief introduction to the major issues and a conclusion that includes a broader overview and assessment of the material discussed within the chapter. A general reader can read the first and last chapters of the book as well as the beginning and end of each chapter to get an idea of the issues discussed and their relevance, whereas the specialist can delve into the details of the arguments presented within the chapters. I also have provided catalogues in Appendix 2 listing all of the documented examples of a particular technique, many of which are not discussed in the text. For those who want to pursue the subject further, these tables provide detailed information about every entry along with bibliographic references. In addition, I have included in Appendix 1 a catalogue of the main monuments discussed in the text and a map with their locations (Map 1, p. 4). For readers not familiar with a particular monument, Appendix 1 provides a catalogue with an introduction to each one followed by a list of the relevant vaulting techniques with cross-references to discussions in the text. A glossary of technical terms used is also provided at the end of the book.

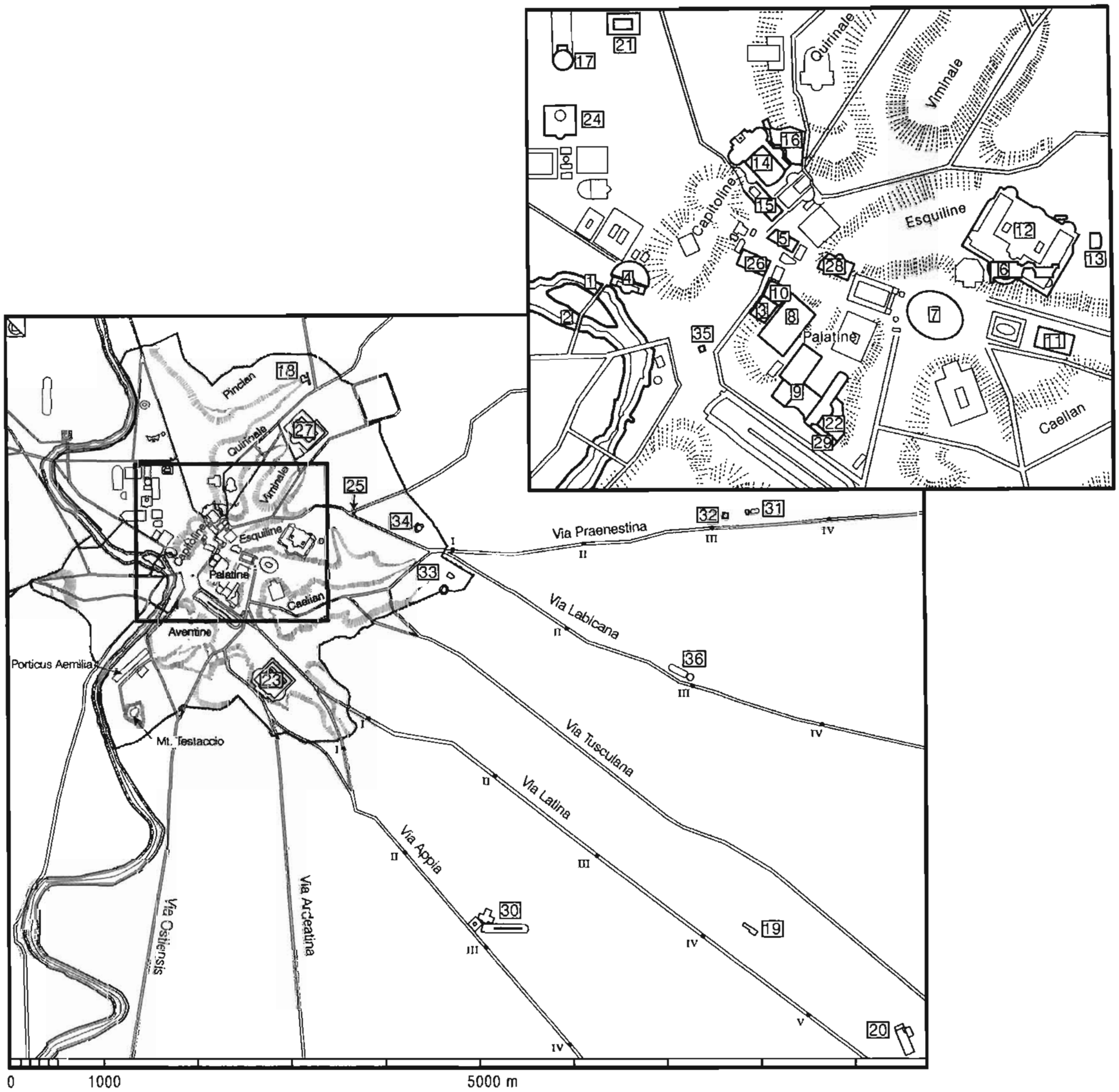
THE NATURE OF ROMAN CONCRETE

Roman concrete, or *opus caementicium*, is different from what we think of today as concrete. The word *caementa* means rough, unhewn quarried stones and refers to the rubble of fist-sized pieces of stone or broken brick that were used in the mortar as aggregate. As implied by its name, the concrete in ancient Rome is more akin to a type of mortared rubble (Pl. II) than to modern concrete, which consists of mortar mixed with an aggregate of much smaller stones usually ranging in size from a pea to a walnut. The way that ancient and modern concrete is put in place is also different: Modern concrete is literally poured into place over a network of steel reinforcing bars, whereas the *caementa* and mortar of Roman concrete were laid separately, by hand and trowel. In both ancient and modern concrete construction, some type of structure, or centering, is necessary to contain and model the wet mortar until it sets and gains strength.

The mortar of the Romans was stronger than the earlier mortar used in Greek architecture because of the addition of a local volcanic material called pozzolana, which creates a chemical reaction that results in a mortar much more tenacious than simple lime mortar. Furthermore, pozzolana mortar is hydraulic and sets underwater. Mortared construction was used outside of Rome and Italy, but locally available ingredients were often substituted. Because each ingredient has a unique effect on the final mixture, distinguishing between mortars from different areas is critical. For example, both O. Lamprecht and R. Malinowski provide useful studies of ancient Roman mortar, but their samples are not from Rome itself.[2] In recent years, Italian engineers and geologists, often working with preservationists, have become more active in the analysis of mortar and concrete samples from buildings in Rome and Ostia, and, in Chapter 3, I have incorporated these results in an effort to provide the most relevant information regarding the local mortar.

CONCRETE VAULTING DURING THE REPUBLIC

The development of concrete vaulting during the Republic has been covered admirably by W. L. MacDonald and others,[3] so in what follows I limit myself to a brief introduction of the major developments before the time of Augustus. Pozzolana mortar and concrete walls probably developed as early as the late third century B.C.,[4] but the use of concrete for vaulting came somewhat later. One of the earliest and most spectacular examples of concrete vaulting in central Italy is at the Sanctuary of Fortuna Primigenia at



1 Pons Fabricius
2 Pons Cestius
3 Horrea Agrippiana
4 Theater of Marcellus
5 Basilica Aemilia
6 Domus Aurea
7 Colosseum
8 Domus Tiberiana
9 Domus Flavia/Augustana
10 Domitianic Vestibule
11 Structure under San Clemente
12 Baths of Trajan
13 Sette Sale
14 Forum of Trajan
15 Forum of Caesar
16 Trajan's Markets
17 Pantheon
18 Pavilion in Horti Sallustiani
19 Villa alla Vignaccia
20 Villa di Sette Bassi
21 Hadrianeum
22 Severan Baths on Palatine
23 Baths of Caracalla
24 Baths of Agrippa
25 Nympheum Alexandri
26 Basilica Julia
27 Baths of Diocletian
28 Basilica of Maxentius
29 Baths of Maxentius on Palatine
30 Villa of Maxentius
31 Tor de'Schiavi
32 "Villa of the Gordians"
33 Sessorian Palace
34 "Temple of Minerva Medica"
35 Arch of Janus
36 Mausoleum of Helena

MAP 1. Map of Rome and environs locating the major monuments discussed in the text.

Palestrina (ancient Praeneste). The sanctuary has been known since the Renaissance, but the upper sanctuary was only uncovered after bomb damage during World War II revealed parts that had been built into modern structures. The dating of the sanctuary has been controversial. It originally was assumed to have been built after Sulla's occupation of the city in 82 B.C.,[5] but G. Gullini in a monograph on the monument proposed a mid-second century B.C. date, to which G. Lugli strongly objected.[6] A. Degrassi, in a study of the epigraphic material, supported a pre-Sullan date of the monument but was unwilling to accept such an early one and proposed that the monument was constructed in the last decade of the second century B.C.[7] The weight of the evidence leans toward a late second century date, which makes it the earliest of a series of spectacularly sited, terraced sanctuaries that employed concrete vaulting including the sanctuaries of Hercules Victor at Tivoli, of Jupiter Anxur at Terracina (Fig. 1), and of Hercules Curinus near Sulmona, all of which have been dated to the first half of the first century B.C.[8]

Early examples of vaulting in Rome itself are rare, in part because larger and more impressive imperial buildings replaced many of them. Traditionally, the earliest datable concrete vaulted structure in Rome has been assigned to the remains of a large structure located between the Tiber and Monte Testaccio, but once again controversy reigns. In 1934, G. Gatti associated this structure with a fragment of the Severan Marble Plan that clearly represents the visible remains. A partial inscription [—]LIA survives on the fragment, and he interpreted it as the Porticus Aemilia,[9] which Livy tells us was reconstructed in 174 B.C.[10] Recently, this reading of the inscription and the association of it with the remains of the Porticus Aemilia has been challenged,[11] potentially leaving us with no datable concrete vaulted remains from second-century-B.C. Rome.

1. Sanctuary of Jupiter Anxur (first half of the first century B.C.). View of concrete vaulted platform overlooking the Tyrrenian Sea at Terracina. Fototeca Unione c/o American Academy in Rome, neg. #5139.

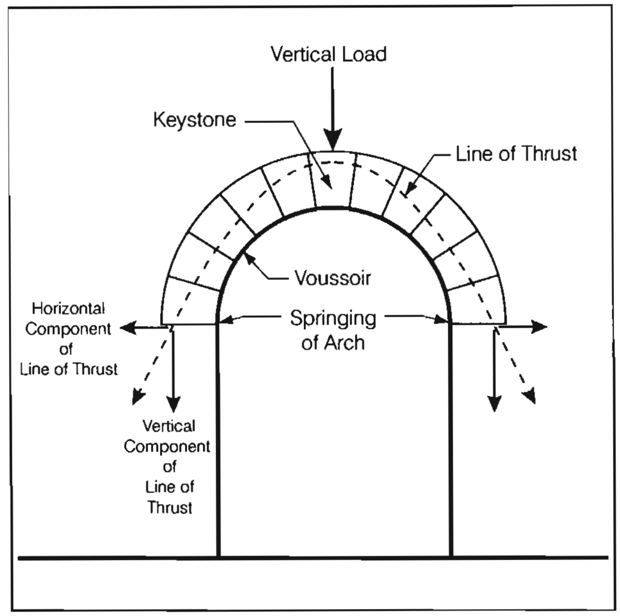
By the first half of the first century B.C., concrete vaulting was firmly established in Rome, as it was in the towns of central Italy. The Tabularium, which is dated by an inscription to 78–65 B.C.,[12] was one of the earliest concrete vaulted structures in the heart of Rome. Like the hilltop sanctuaries, it served the structural purpose of shoring up the face of the Capitoline. Within its façade of peperino blocks, the Tabularium contained a series of pavilion vaults and barrel vaults.[13] Some two decades later, Rome received its first permanent theater dedicated by Pompey in 52 B.C. In breaking a long-standing tradition within the Senate of not allowing permanent theaters or amphitheaters to be built as places for large gatherings, Pompey opened the gates for experimentation in vaulting for the substructures of such buildings. Some early innovations in vaulting techniques can be found in similar structures, such as the Theater of Marcellus and the Colosseum.

So, what prompted the early development of concrete vaulting in central Italy? As seen earlier, the most spectacular early uses were in the hilltop sanctuaries, but by the first century B.C., vaulting also could be found in other types of structures such as the storage/market buildings at Ferentino and Tivoli and in bath buildings at Pompeii.[14] Part of the answer certainly lies in the available natural resources and in the financial resources generated by conquests outside of Italy by this time, but cultural influences also affected the early development. The hillside settings of the terraced sanctuaries were influenced by Hellenistic Greek types, such as the Sanctuary of Athena at Lindos on Rhodes (second century B.C.) and the Sanctuary of Asclepius at Cos (first half of second century B.C.).[15] Incentives to use the new vaulted construction also came from within Italy itself. Concrete vaulting provided both an economical and fireproof means of storage for the goods coming from the conquered territories, and it was a particularly suitable material for enduring the constant moisture present in bath buildings that were becoming increasingly popular.

By the time of the Augustan peace when routes of transport were opened and craftsmen flocked to Rome, concrete vaulting had become common, and during this period the early attempts at more sophisticated vaulting techniques began to appear. The preceding century had provided the context for the acceptance of vaulting, but once the scale of the buildings began to grow and the spans became larger, the builders had to deal with structural challenges that had not been relevant in earlier times.

STRUCTURAL BEHAVIOR OF CONCRETE VAULTS

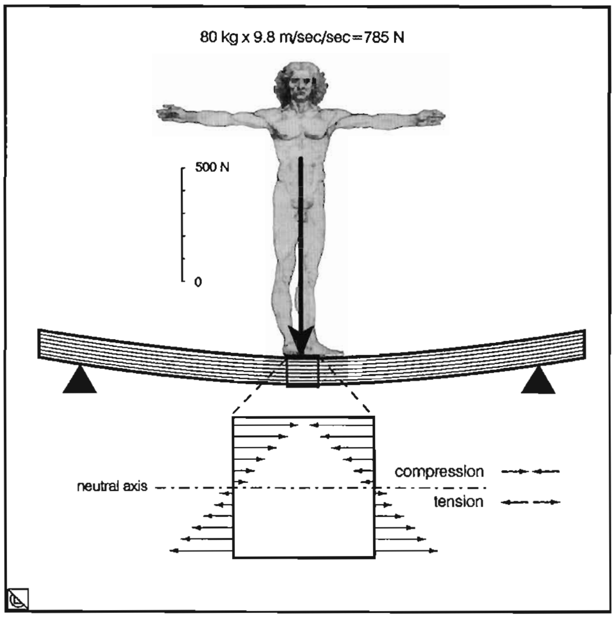
Roman concrete vaults are known for their longevity, and many visitors to Rome today often ask why our



2. Diagram showing principle parts of an arch and its behavior.

modern reinforced concrete structures seem to have such limited life spans in comparison to ancient ones. The success of Roman concrete structures is often attributed to the strength of the pozzolana mortar. In fact, this is only part of the explanation. Just as important is the relationship between the masses and forms making up the structure. Structural form was a critical factor in the success of Roman buildings. The interplay between form and material was ultimately the key to longevity.

The arch, which was originally developed for stone construction, was the basis for the formal development of concrete vaulting. Recent findings show that builders in Rome were using arches of cut stone voussoirs by the sixth century B.C.[16] Voussoirs are wedge-shaped stones that make up an arch (Fig. 2). The radiating joints between the voussoirs serve to direct the weight of the arch and anything it supports toward the sides and away from the opening under the arch. The result is that the arch pushes out at its springing, and this outward thrust must be countered or controlled in some way. If the arch is built into a wall, the



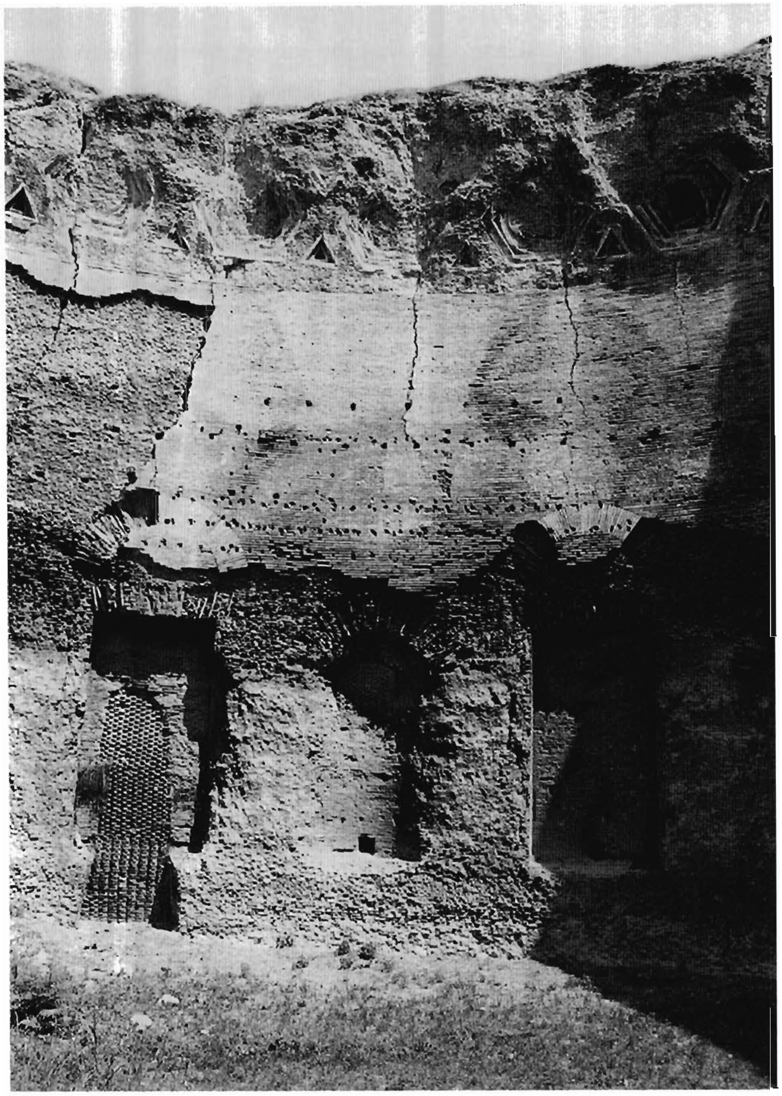
3. Diagram showing the stress patterns in a beam with a point load applied at center.

surrounding masonry acts as a buttress to contain the horizontal thrust.

The strength of any material is measured in terms of *stress*, which can occur as compression (compressive stress) or tension (tensile stress). Compressive stress results when the atoms in a material are pressed together in the direction of the converging forces. Tensile stress results when a material is stretched so that the atoms are pulled apart in the directions of the opposing forces. The example of the man on the beam in Figure 3 shows both types of stresses within the beam. As the beam bends downward under the man's weight, the upper half is in compression because the top surface is squeezed together and becomes shorter, and the lower half is in tension because the lower surface is stretched. At a point in the middle of the beam, there is a neutral axis that is not undergoing tension or compression. The strength of the beam is its ability to resist the different types of internal stresses that occur under various loading situations. Because both concrete and stone are very strong in compression and weak in tension, the arch provides a means of spanning a distance so that the stresses within the material remain in compression. Tension can develop within an arch, but it can be controlled by the form, size, and loading pattern of the arch. The mechanics of arch and vault behavior and methods of structural analysis are explored further in Chapter 8.

Concrete vaults take forms similar to arches built in cut stone, but their behavior is somewhat different. The forces are not transferred by means of the joints between individual voussoirs but, rather, through the mortar between the pieces of *caementa*, which by the imperial period were laid in horizontal courses. As long as the mortar is strong enough to resist any tensile stresses that develop as a result of these factors, the concrete can act as a solid monolithic block once it has cured and gained its strength, and lateral thrusts will not occur. If too much tension develops then cracks occur and the vault begins to push outward, or to display lateral thrust, on its supports, just like the voussoir arch. As long as the thrust is sufficiently countered the structure will remain stable, but if the supports cannot resist the lateral thrust the structure collapses. The success of the Roman builders was in their ability to control the outward thrust of vaulted structures through the choice of form and materials.

The modern understanding of the behavior of Roman concrete has undergone changes during the past century. J. H. Middleton, writing at the end of the nineteenth century, commented that "the Roman concrete vault was quite devoid of any lateral thrust and covered its space with the rigidity of a metal lid."[17] This idea of the monolithic concrete vault that has no horizontal thrust was repeated by such notable scholars as M. E. Blake, J. B. Ward-Perkins, and J.-P. Adam,[18] but it remained controversial throughout much of the twentieth century. It is based on the assumption that concrete made with pozzolana mortar has the strength to resist any internal tensile stresses that could cause cracks to develop. Both

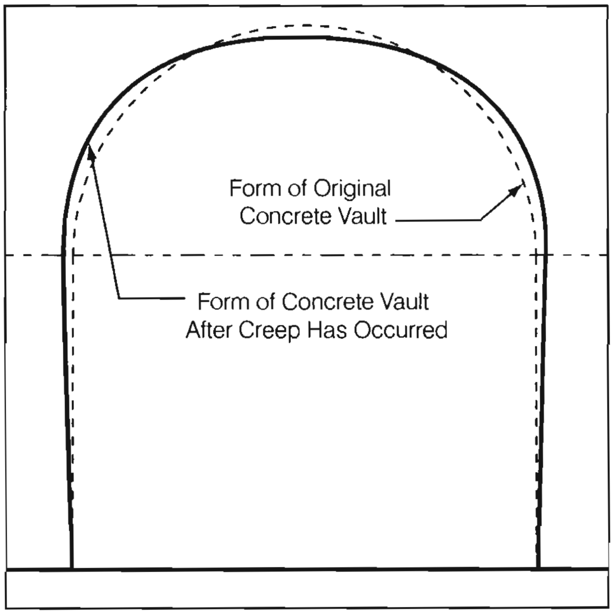


4. Baths of Trajan (A.D. 104–109). Detail of the exedra at section D showing cracks in wall supporting semidome (29.5-m span).

W. L. MacDonald and G. Lugli were more circumspect in their assessment of the structural behavior of concrete vaulting noting that the monolithic qualities actually depend on the size of the vault.[19] One of the more influential studies affecting the understanding of vault behavior has been the extensive documentation of cracking and deformation in the concrete structure of the Hagia Sophia in Istanbul by R. Van Nice, R. Mainstone, R. Mark, and A. S. Çakmak.[20]

With the increased interest in preservation since the end of World War II, more engineers have become involved in the analysis of historical structures. As a result of the analytic approach they bring to the discipline, the traditional view of monolithic concrete long held among some classical scholars has been modified to acknowledge that, in spite of the high-quality pozzolana mortar used by the Romans builders, lateral thrust often occurred and had to be countered.

Roman concrete vaults commonly developed cracks as can be seen in standing remains of many structures,[21] including such imposing ones as the Pantheon, the Baths of Trajan (Fig. 4), and the Basilica of Maxentius. The cracks could occur for a number of reasons. If the tensile stresses within the concrete exceed the tensile strength of the material, cracks will develop. The level of such tensile stresses can be controlled through the judicious design of structural form. However, even when the stresses are normally very low, external factors can cause sudden increases. A common example is a dramatic change in temperature that results in sudden expansion or contraction, which can cause the tensile stresses to spike and a crack to occur.[22] (A similar reaction is observable when a cold egg is dropped into boiling water and immediately cracks.) Moreover, concrete is subject to a phenomenon called *creep*, which is slow deformation over time. In concrete vaulting this usually results in a flattening of the curve of the vault and a spread at the haunches (Fig. 5). The gradual change in form creates changes in the patterns of stresses within the concrete, which can then lead to cracking.



5. Diagram indicating deformation of barrel vault due to creep.

During the second century B.C., when concrete vaulting was in its infancy, the builders were constructing fairly small vaults (typically 5 m or less), which could have acted monolithically, and evidence from the Sanctuary of Fortuna Primigenia at Palestrina (second half of the second century B.C.) suggests that these early builders did not take precautions to counter lateral thrusts.[23] In two places at the sanctuary, vaults were supported on at least one side by a trabeated system of columns and architrave blocks. On the Terrazza degli Emicicli, the concrete vault (3.7 m span) was built of radially laid *caementa* of limestone on the flat upper surface of the travertine architrave (Fig. 6).[24] Metal clamps were not typically used to hold the architrave blocks together, which suggests that the builders did not expect the concrete to push laterally against them but, rather, to bear straight down. A similar condition occurred

6. View of the "Terrazza degli emicicli" of the Sanctuary of Fortuna Primigenia at Palestrina (second half of the second century B.C.).

elsewhere in the complex on the Terrazza della Cortina (Fig. 7), except there the vault was built of *caementa* of the lighter local tuff.[25] Both examples had coffers in the vault, which G. Gullini suggested were intended to lighten the vault while creating a type of ribbing between the coffers.[26] In this early example of concrete vaulting, the builders evidently assumed a degree of strength in the concrete that later imperial builders did not.

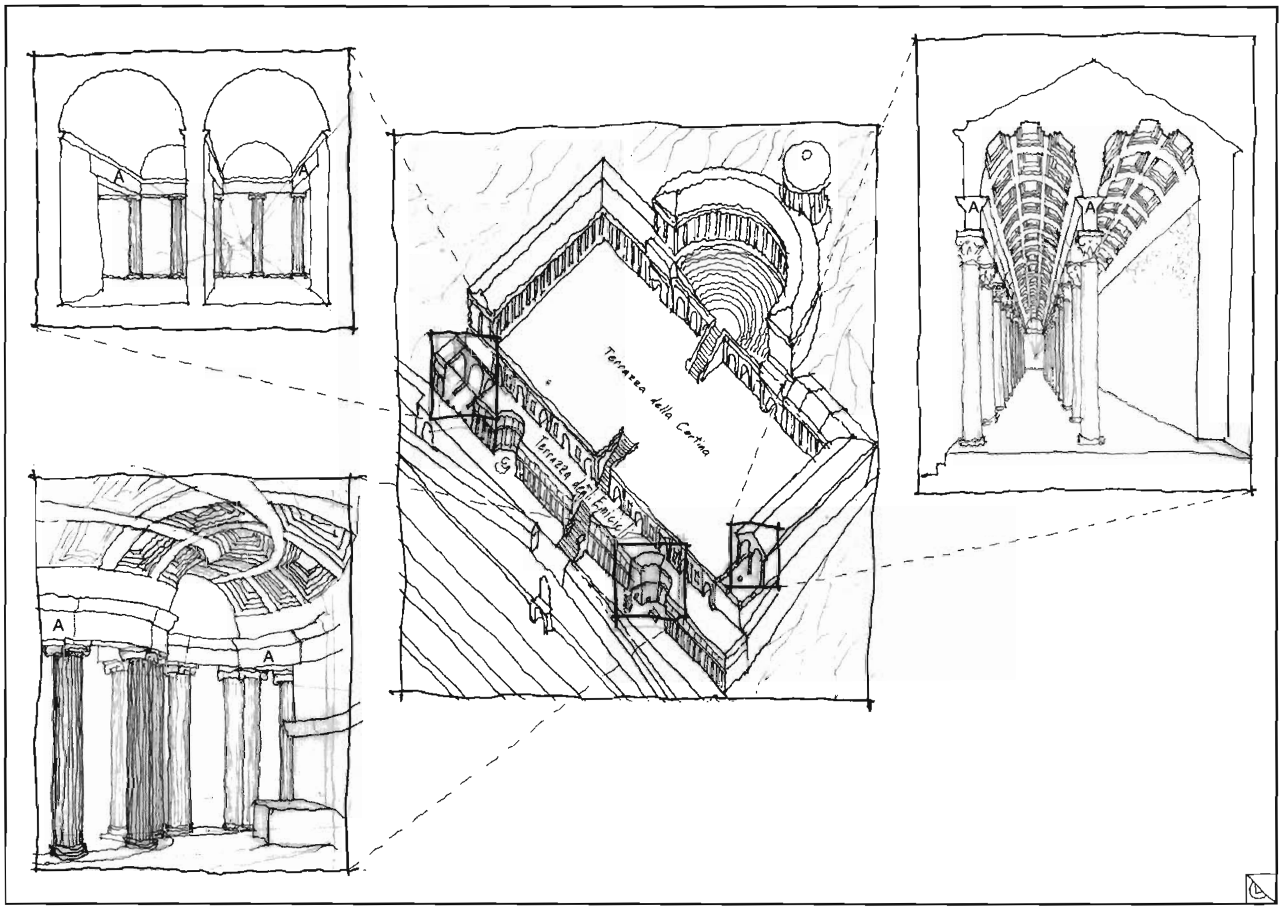
By the time of Augustus, the builders clearly realized that once the span of the vaults increased and the support structure became less massive, they had to take some precautionary measures to counter any lateral thrust that could develop. They must have learned (perhaps the hard way) that once cracks developed in a vault, it began to push out on its support structure and would collapse if the thrust was not countered. We have little evidence for those experiments that did not work, but by this time builders had begun to think of ways of reducing the horizontal thrust, such as choosing lightweight stones as *caementa* and using metal clamps to stabilize the stone support structure.

ROMAN MATHEMATICAL AND ANALYTICAL BACKGROUND

With the adoption of concrete, the methods of calculating the necessary materials for building projects changed. For cut stone vaults, the architect would have calculated the number of blocks needed, whereas for concrete vaults he would have calculated the volume of the vaults and ordered a certain amount of lime, pozzolana, and *caementa* depending on the proportions of each he intended to use in the concrete mixture.[27] This type of calculation would have required measuring units (as opposed to number of blocks), which for the Roman builders was typically in terms of *pedes* (Roman feet = RF), which could be divided into either 12 *oncia* (inches) or 16 *digiti* (digits). Measuring sticks often had two sets of divisions, one for inches and one for digits.[28] The Roman foot varied somewhat from place to place, but it was usually about 29.5 cm, which is somewhat smaller than the modern foot (30.5 cm).

The appearance of concrete vaulting comes after the death of Archimedes (212 B.C.), who provided the mathematical means of estimating volumes of spheres and the areas of conic sections. Such calculations were clearly relevant for concrete construction by the first century A.D. Heron of Alexandria, who gave credit to Archimedes, included a section in his *Stereometrica* explaining how to calculate amounts of materials for the curving forms of various types of vaults.[29] Heron also wrote a treatise called *On Vaulting* (*Camarika*), about which Isodorus of Miletus (mid-sixth century A.D.) wrote a commentary.[30] Unfortunately, neither Heron's treatise nor Isodorus's commentary has survived, but the fact that Heron devoted an entire work to the subject in the second half of the first century A.D. just at the time that concrete vaulting became the norm in imperial Rome is in itself significant. Archimedes was famous for shunning the practical uses of his theoretical discoveries, but the Romans had no such qualms.[31]

Advances in mathematical and geometrical knowledge also would have affected the understanding of the relationships between masses, which govern structural form. One of the fundamental principles for understanding the behavior of masses is the concept of the center of gravity, another Archimedean contribution. The center of gravity of an object is the point at which the object will balance as if the whole weight of the object is concentrated at that point, as on a fulcrum. The development of modern structural theory was ultimately based on this concept (see Chapter 8). By the first century A.D., Heron was concerned with explaining it. In solving various structural problems



7. Sanctuary of Fortuna Primigenia at Palestrina (second half of the second century B.C.). Sketches showing details of areas with colonnades supporting concrete vaults. The architraves are marked with "A."

in his *Mechanics*, he was clearly thinking in terms of geometry, the balancing of masses, and the ratios that governed the relationships between bodies.[32] If his treatise on vaulting had survived, we surely would have found similar thought processes as the ones expressed in the *Mechanics*, although there is no evidence to suggest that the Romans ever developed the means to calculate actual thrusts. Archimedes may have provided a way of thinking about arched and vaulted structures, but ultimately the Romans' control of their materials and forms must have come through a combination of experimentation on the building site and the understanding of basic geometrical principles.

Heron's interest in vaulting is representative of the change in attitude toward vaulting that took place during the first century. Vitruvius, writing toward the end of the first century B.C., barely mentions vaulting in his treatise, although he does give space to the materials of concrete in Book 2. By the time Heron was writing during the second half of the first century A.D., vaulting was significant enough to have warranted its own treatise. The great fire in Rome under Nero in A.D. 64 is often seen as a turning point in the development of concrete construction, but the turning point it represents is not so much in the immediate creation of new vaulting *techniques* as it is in a new *attitude* toward design and the control of light and space. Concrete offered the potential for new forms and combinations of space that eventually prompted the development of new and innovative construction techniques. Heron was writing at the time when this transition was in full swing. Unfortunately for those of us interested in vaulting, Heron's treatise was lost and Vitruvius lived just a bit too early.

MATERIALS, TRANSPORT, AND PRODUCTION

The choice and availability of materials played an important role in the creation of large spanned vaults. Rome lies along the Tiber River between two volcanic districts, the Monti Sabatini to the north and the Colli Albani to the south (Map 2). These volcanoes produced a variety of building stones used by the Romans: dense lavas for road building, heavy tuffs for cut stone construction, lightweight tuffs for vaulting, and pozzolana for mortar. Sedimentary stones, such as limestone and travertine, for making the lime for mortar were found in central Italy and in the Apennines. In addition, the clay for bricks, which became a fundamental building material during the Empire, was abundant in the Tiber and Aniene river valleys. The tall fir trees from the Apennines and southern Italy and the rich forests of hardwoods, such as oak, elm, and chestnut, supplied the timbers for scaffolding and centering and the fuel for lime and brick kilns. The Tiber and its tributaries provided an efficient means of transport for materials from inland areas as well as a connection to the port city of Ostia where imported materials arrived. The concrete vaulted structures of imperial Rome are in part a result of a fortuitous geological environment rich in natural resources.

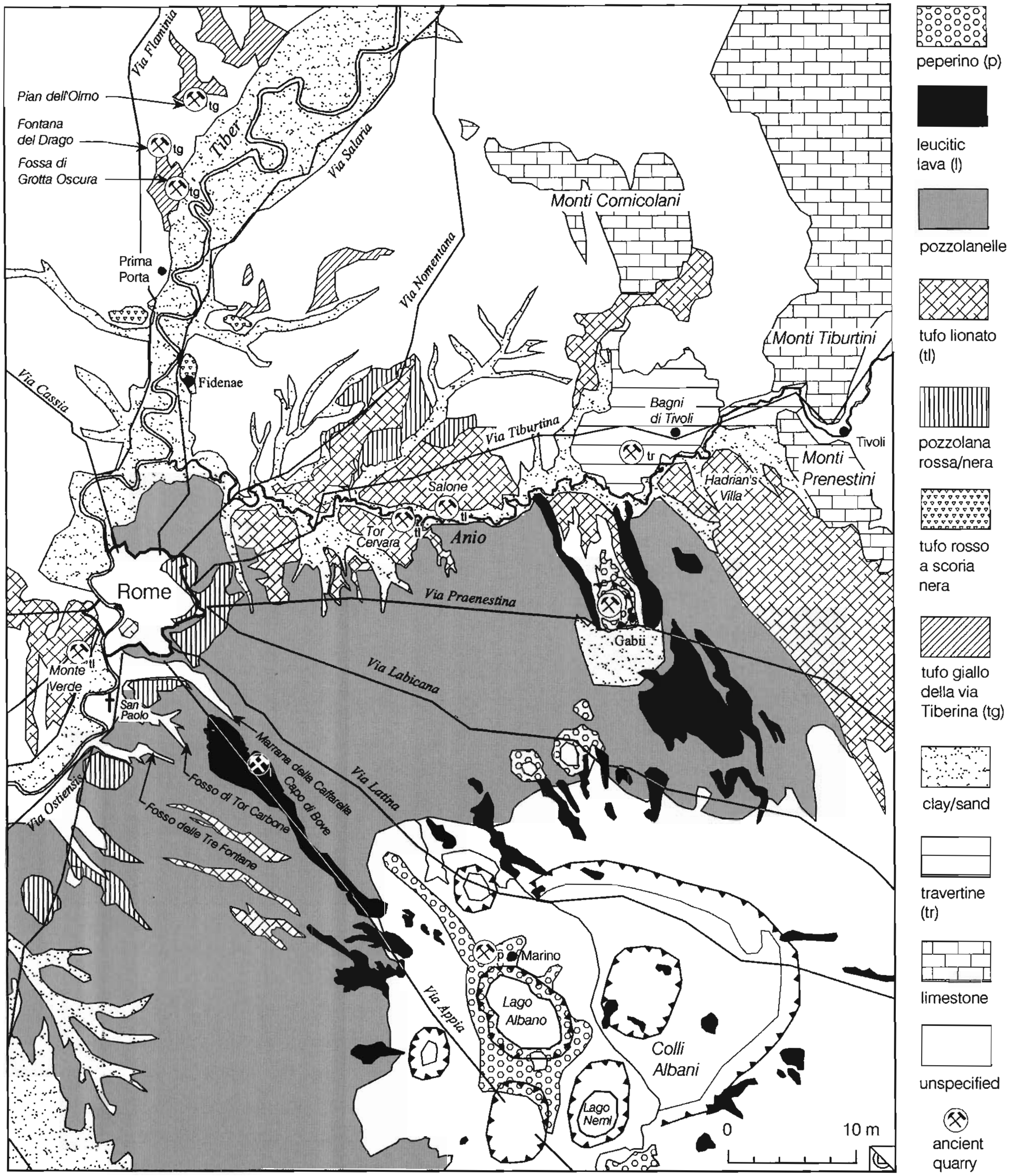
An understanding of the geology of the volcanic areas in Italy is important to the study of local building materials. The geological information on which archaeologists have typically relied has its roots in the seminal works of T. Frank (1924), M. E. Blake (1947), and G. Lugli (1957),[33] but advances in the mapping and dating of the volcanic activity in Italy in the past half century and particularly in the past decade have yet to be integrated into much of the archaeological literature. A difficulty that arises for the present-day archaeologist interested in the geology of Roman building materials is that the terminology used in the standard archaeological works is quite different from the geological nomenclature, which in itself has variations. I use the modern Italian geological names of the various volcanic materials employed by the ancient Roman builders and provide the equivalent archaeological terms in the Glossary. In this study, I avoid the term "tufa," which has traditionally been adopted by English-speaking archaeologists describing the stone made of volcanic ash, in favor of "tuff," which is the more precise and the preferred geological term, as "tufa" also can refer to a type of sedimentary stone. I use the Italian term "*tufo*" when referring to specific named types of tuff in Italy (e.g., *tufo lionato*).

The critical role played by the supply of building materials to a project has recently been highlighted by J. DeLaine, who emphasizes the importance of the interplay between geology and topography in the extraction and transportation of the materials, which in turn affects the cost and ultimately the choices made by the builders.[34] For example, in her analysis of the cost of the Baths of Caracalla, DeLaine notes that about a third of the cost results from building materials and their transport.[35] The supply network involved a variety of people at different levels of society, all of whom stood to gain financially in the process of supplying materials for imperial projects: the manual laborers who extracted the material, the property owners from whose land it was extracted, and the carters and boatmen who delivered it. As a brief introduction, I present here the main building materials referred to in this study and provide an overview of the way in which they relate to the local transportation networks.

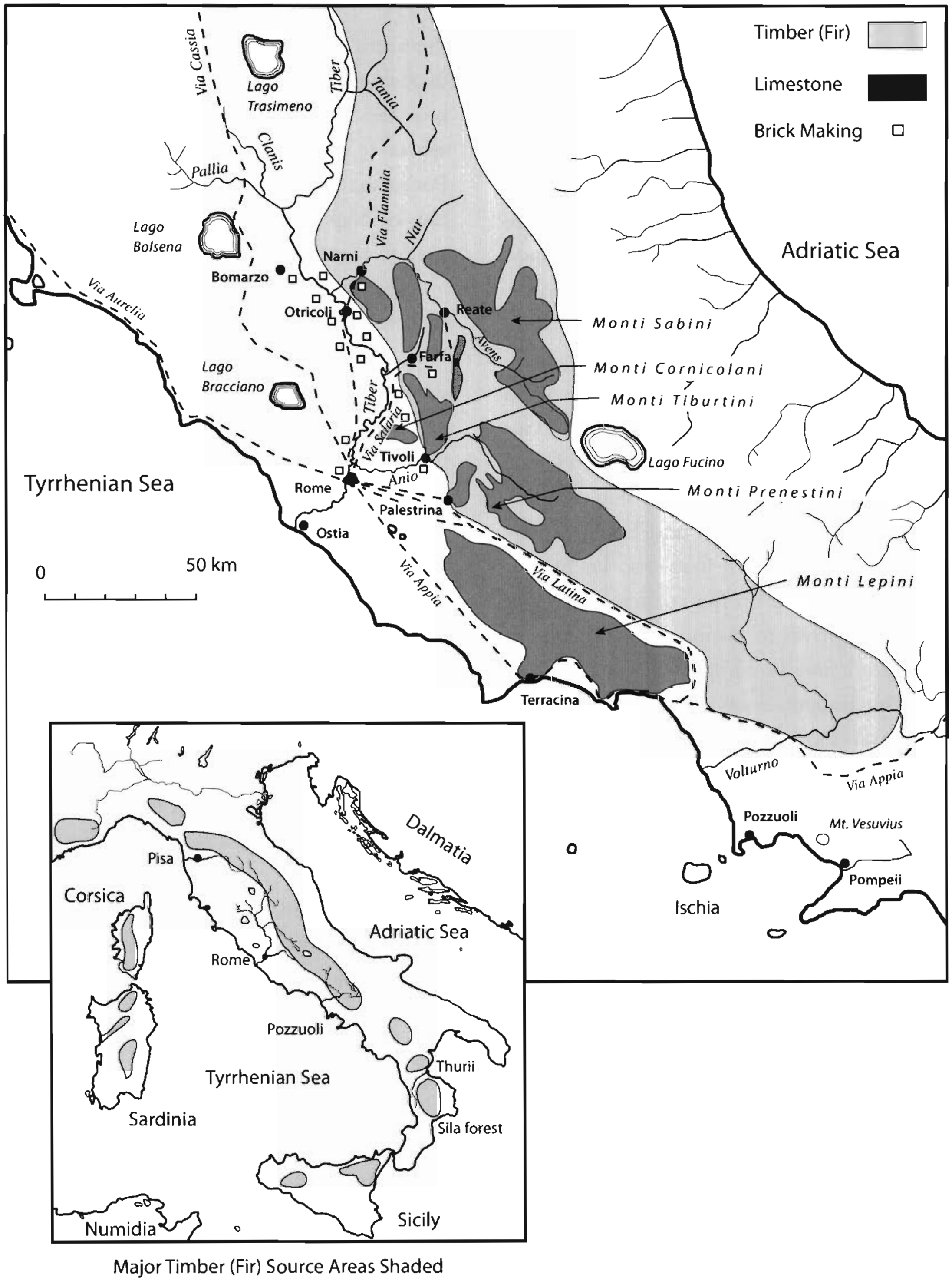
Various types of tuff found locally around Rome were used for the *caementa* in vaulting (Pl. I). The most common type is a reddish brown variety called *tufo lionato* (traditionally called Aniene tufa), which is a product of the Colli Albani district. It was quarried extensively along the Aniene river,[36] which provided easy transportation into the city.[37] Outcroppings also occur to the south of Rome, particularly in the area known today as Monteverde on the right bank of the Tiber.[38] A less common type but evidently one more prized for vaulting because of its light weight is the yellow tuff known as *tufo giallo della via Tiberina*, which is a product of the Sabatini district. Ancient quarries of this tuff have been found about 15 km to the north of Rome along the Fosso di Grotta Oscura, from which the traditional archaeological name, Grotta Oscura tufa, is derived. Other quarries also occur further to the west at Fontana del Drago and to the north at Pian dell'Olmo (Map 3, p. 14).[39] The *tufo giallo della via Tiberina* often has large cinderlike scoria and pumice fragments within the ash matrix, which makes it lighter (1,350 kg/m^3) than the *tufo lionato* (1,600 kg/m^3). Another Sabatini tuff called *tufo rosso a scorie nere* (traditionally Fidenae tufa) also is found in some vaults. It is characterized by large pieces of black pumice and occurs along the Tiber near Prima Porta and near the ancient city of Fidenae (Map 3 and Pl. I). It, too, was lighter (1,350 kg/m^3) than the *tufo lionato*, because of the scoria in its matrix.

MAP 2. Map of Italy showing the major volcanic districts and the provincial divisions under Diocletian. Shaded circle indicates 100-mile jurisdiction of *praefectus urbi*.

Other volcanic stones sometimes used in vaulting include peperino, a denser and heavier (2,250 kg/m^3) type of tuff usually found along the rims of craters. The two types used in Rome were *lapis Albanus* and *lapis Gabinus*, from the craters at Marino on Lago di Albano and at Gabii, respectively. The quarries of both types are located about 20 km from Rome, but those at Gabii are 5–6 km from the Aniene, whereas the *lapis Albanus* quarries have no nearby river transport available.[40] Rarely, a very dense and heavy



MAP 3. Geological map of Rome and environs showing locations of major building materials used in concrete vaulting. Deposits of materials not used by Roman builders are not shown.



MAP 4. Map of Italy showing locations of major sources of timber and limestone.

type of leucititic lava (2,800 kg/m^3), commonly called *selce*, was used in vaulting. It is extremely hard and difficult to quarry and was used primarily for road building or as *caementa* in foundation walls. The main quarries were from the Capo di Bove flow along the Via Appia, but small flows also occurred elsewhere around the Colli Albani craters. Like the *lapis Albanus*, it would have been transported to the city by road.

Occasionally one finds very lightweight *caementa* used for vaults in Rome, usually for large or structurally precarious ones. The most common type was a reddish to dark brown, vesicular scoria from Vesuvius on the Bay of Naples. This material is often referred to generically as pumice in the archaeological literature, but it is somewhat coarser and heavier (750–850 kg/m^3) than true pumice (600–700 kg/m^3). It would have been shipped up the coast to Ostia and then transported upriver to Rome. This was one of the only nondecorative building materials imported from outside the immediate environs of Rome. Some local pumices, varying in color from white to yellow to gray to black, were used as *caementa*. Most if not all were products of the volcanic districts north of Rome and would have been transported down the Tiber.

The pozzolana used in the mortar is a local product of the Colli Albani district. It comes in three varieties: *pozzolana rossa* (red), *pozzolana nera* (black), and *pozzolanella* (grayish) (Pl. III). Each belongs to a different volcanic event. Stratigraphically the red (1,600–1,900 kg/m^3) is in the lowest layer, followed by black (1,340 kg/m^3), with the *pozzolanella* (1,360–1,670 kg/m^3) on top (Pl. IV). The last was often quarried in open air and was probably the first to be exploited. It was, however, an inferior product, and the Romans soon began to use the deposits of *pozzolana rossa* and *nera* by means of underground tunneling. Access in antiquity was typically gained from the side along valleys such as the Marrana della Caffarella, Fosso di Tor Carbone, and Fosso delle Tre Fontane to the south and east of Rome (Map 3, p. 14).[41] Major deposits of *pozzolana rossa* up to 10 m thick are located near the basilica of San Paolo Fuori le Mura, from where it gets the name "pozzolana di San Paolo." Pozzolana also was produced by the volcanoes on the Bay of Naples, but there is no evidence that it was used in imperial Rome (see Chapter 3).

Travertine (2,450 kg/m^3) is a sedimentary stone that was often used in cut stone construction because of its attractive creamy white color and its hard and durable nature. Although not typically used in the vaulting itself, it sometimes played a role in the supporting structure. It is found in great quantities near Tivoli (ancient Tibur) and was therefore called by the Romans *lapis Tiburtinus*. Anyone traveling out to Hadrian's Villa has no doubt experienced the sulphuric odors of the hot springs of Bagni di Tivoli. These odiferous springs are the source of the nearby travertine quarries, which were once part of a basin in which the calcium carbonate in the water supplied by the hot springs precipitated creating an 80-m thick stratum of travertine. These quarries were the main source of travertine for the ancient Romans and are still today among the top suppliers of travertine worldwide.[42]

Lime is the main ingredient of mortar and is derived from burning stones containing calcium carbonate ($CaCO_3$), usually limestone, travertine, or marble. Limestone was probably the major source of lime for Rome during the first three centuries A.D., but it was not local to the immediate environs. The nearest sources of limestone would have been the mountain ranges to the northeast of Rome: Monti Tibertini, Monti Cornicolani, and Monti Sabini reaching as far as Narni, and those to the southeast: Monti Prenestini and Monti Lepini reaching down to Terracina (Map 4), all of which lie within an 80-km radius of Rome.[43] Lime is a processed material. It first had to be fired, which required fuel, and then it had to be slaked. The processing resulted in a material that was more expensive than the pozzolana and tuff.[44] Pliny the Elder lamented that the chief reason for the collapse of buildings was from skimping on lime,[45] and indeed Faventinus, writing in the early fourth century A.D., made the point that lime was the most expensive ingredient used in mortar.[46]

Brick (1,750 kg/m^3) became an important material for vaulting by the end of the first century A.D., and the development of the brick industry had a great effect on the vaulting techniques in Rome. The bricks were made in three basic sizes $\frac{2}{3}$ RF (*bessalis*), $1\frac{1}{2}$ RF (*sesquipedalis*), and 2 RF (*bipedalis*). The earliest brick wall facings in Rome began to appear during the late Republic and were made of roof tiles with the flanges knocked off, as can be seen in the facing of the tomb of Caecilia Metella on the Via Appia.[47] By the time of Claudius the roof tile manufacturers were branching out into bricks, and wall facing made of triangular bricks sawn from *bessales* or *sesquipedales* began to appear then.[48] Within a century, the brick industry had become a highly developed organization involving people from various levels of society.

The clay used for bricks and tiles was the old marine clay of the Pliocene era (2–13 million years ago) that underlay the volcanic material of later periods, and it was typically accessed along riverbeds that had eroded the more recent materials, laying bare the Pliocene clay. Stamps on the bricks provide information both on the general locations of the clay beds and on people involved in the industry (discussed later). Within the city, the Vatican and Trastevere were known for their clays.[49] Outside of the city, the clay beds tended to be located along the Tiber and Aniene river valleys at least as far as 70 km north of the city around present-day Bomarzo.[50] Ongoing research into locations of kiln sites and the mineralogical and chemical makeup of the clays will hopefully yield further information on the landholdings north of Rome.[51]

Rome also was surrounded by forests that provided fuel for firing bricks and lime and for building the wooden centering necessary to mold the concrete vaults. For the largest concrete vaulted structures, the most prized wood would have been long timbers of fir, which was considered by both Vitruvius and Pliny the Elder to be light, strong, and stiff.[52] Fir was found in the lowland areas on the west side of Apennines facing Campania and Etruria as far north as Pisa.[53] It also was grown in southern Italy in the Sila forest and on the island of Corsica (Map 4, p. 15).[54] The availability of large timbers seems to have declined during late antiquity. In the fifth century A.D., Sidonius implies that there had been too much timber taken from the Apennines,[55] though R. Meiggs cautions against placing too much emphasis on deforestation.[56]

Transportation for building materials to Rome was provided by the Tiber and its tributaries as well as by an extensive and well-built road system. The Tiber connected Rome to Ostia on the coast and ran inland as far north as Arezzo. Its tributaries, the Pallia and Clanis Rivers, serviced the area west of the Tiber between the Lago di Bolsena and Lago Trasimeno, the Aniene area east to Tivoli, and the Nar and Tania areas east of the Tiber into Umbria. The points at which the rivers and roads intersected often were serviced by river ports, as at Otricoli and Narni, to facilitate transport of goods south to Rome.[57] These tributaries to the east of the Tiber also would have been used for transport of lime and limestone from the Monti Sabini. The upper reaches of the Tiber above the confluence of the Tania and Clanis were not always navigable, but Pliny the Elder noted that a system was devised by which an ingenious series of dams collected water over a period of nine days after which it was released to create a navigable waterway; otherwise, the upper Tiber was suitable only for logs and rafts.[58] Strabo emphasized the importance of the Tiber and its tributaries, the Nar, Tania, and Clanis, for supplying timber to Rome during the Augustan period, and presumably much of this could simply be floated without the need for boats.[59] The areas to the south and east of Rome did not have the advantage of waterways, but they were serviced by the roads radiating out from the city, the Appia, Latina, Labicana, and Praenestina (Map 4, p. 15).

The method of transportation would have affected the costs of materials, which in turn could have had an effect on their use. Based on evidence from Diocletian's Price Edict, DeLaine has calculated the ratio of costs for transportation by means of sea:downstream: upstream:oxcart as 1:3.9:7.7:42.[60] Indeed, transport of large timbers was a major factor in their availability. In describing the timbers cut from the Sila forest in south Italy during the Augustan period, Dionysius of Halicarnassus says that the largest timbers are cut as near as possible to the sea or river with timbers further away being cut into smaller pieces on site and then transported.[61] One of the few lime kiln complexes to have been excavated that may have supplied the city is located at Lucus Feroniae (c. 10 km north of the Grotta Oscura tuff quarries) near a river port on the Tiber, which would have provided easy access to the city.[62] Likewise, the proximity of quarries and brickyards to river transport would have affected transportation costs.

THE BUILDING INDUSTRY IN ROME

During the Republic, public building was overseen by the aediles or the censors who let out bids for contracts to private contractors, *redemptores*.[63] Augustus, as part of his urban renewal program, established commissions to oversee the care of the public buildings (*cura operum publicorum*), the water supply (*cura aquarum*), the roads (*cura viarum*), and the bed of the Tiber (*cura alvei Tiberis*).[64] The care and maintenance of roads and the Tiber valley ensured the viability of building materials into Rome. The *cura operum publicorum* oversaw the upkeep of public property,[65] although whether it also was in charge of the construction of new buildings is less clear.[66] The result of Augustus's reorganization was the creation of an infrastructure for the supply and maintenance of the city, which provided a level of continuity and centralized control that had not existed previously, and this certainly would have aided in the organization of labor and the supply of materials to the capital.

During the imperial period, the labor for both new building projects and maintenance of existing structures continued to be acquired through the letting out of bids to private contractors as attested by Frontinus, writing from his perspective of water commissioner.[67] The use of *redemptores* on imperial building projects is also borne out in various funerary inscriptions in which the deceased identifies himself as a contractor for imperial or public works (see later). A common misconception is that the construction of large imperial building projects such as the Colosseum or the imperial baths was made possible by large numbers of slave laborers taken from conquered territories. The implication of this assumption is that the government did not have to pay for labor other than the upkeep of the slaves. This assumption, however, has been shown to be a simplistic view of the use of slave labor in Rome. In 1980, P. Brunt argued that a substantial amount of nonslave labor was used for building projects in Rome,[68] and more recent work on the building industry supports the idea that significant numbers of the free populace in Rome found work on public building projects.[69] These contractors could have staffed their crews with both slave and nonslave labor, but regardless of the social status of the worker, a majority of the crew would have been skilled laborers as opposed to unskilled war captives used for hard labor.[70] Some slave labor could have been involved, but that labor would have come at a cost: both to the contractor who bought and supported (or else rented) the slaves and to the imperial administration who hired the contractor and his crew.

Inscriptions bearing the names of contractors for public and imperial works also reveal that many of them were freedmen or descendants of freedmen from wealthy senatorial families. One example dating from the late first century or early second century is the funerary inscription of the imperial freedman [T. Clau]dius Aug. l. Onesimus, which states that he was a contractor for imperial works (*[rede]mptor operum Caesar(is)*).[71] Another self-identified *redemptor*, Q. Haterius Tychicus, was a freedman of the powerful senatorial Haterius family.[72] He may be the same person who was buried in the tomb of the Haterii. Unfortunately, the *cognomen* of the deceased in the tomb is not preserved to verify his association with Tychicus. Nevertheless, the iconography of the reliefs in the tomb suggests that the deceased may have been involved in the building trade, as was another freedman of the Haterius family, Q. Haterius Evagogus.[73]

Freedmen were bound to their former masters through the Roman institution of *clientela* whereby persons of different social strata had certain obligations for each other's welfare. In the case of freedmen, however, this relationship was formalized by law, and it is often traceable in the epigraphic record through the naming convention for freed slaves.[74] The bond of *clientela* also could have been a significant factor for the advancement of some freeborn building contractors, albeit one that is not so evident from the epigraphic record. Such connections between the members of different social strata would have been beneficial to both parties, with the senatorial land owners providing contacts to the contractor bidding on large state projects and the contractors acquiring materials such as timber, pozzolana, or bricks produced on senatorial properties.[75]

Building contractors often relied on a type of contract called *locatio conductio* (lease and hire). A common type used for building projects was *locatio conductio operis* (lease and hire of units of work), in which the *locator* (patron) lets out a job to be completed by the *conductor* (builder). The contract included a final inspection (*probatio*) and an agreed-on price (*merces*). In this type of contract, the builder took on responsibility for the site until the final inspection of the work (*probatio*),[76] which released him of responsibility. He could negotiate for either a task fee for the whole job or a task rate based on measured intervals. Another method of hiring was through a contract of *locatio conductio operarum*, in which the *locator* (laborer) lets himself out to the *conductor* (patron) for a daily wage or piecemeal wage. In this case, the laborer took no responsibility for the site,[77] but along with less responsibility came less pay. A single project could combine various types of hires depending on the nature of the job.[78]

The inscriptions on brick stamps provide a glimpse into the working relationships between people of different social status in the building industry. Steinby has proposed that the stamps represent a contract of *locatio conductio operis*, whereby the owner of clay beds (*dominus*) contracted for the brickmaker (*officinator*) to make a certain number of bricks that were then the property of the landowner to sell as he (or often she) pleased.[79] The *domini* listed in the stamps were typically of the senatorial class, and the *officinatores* were from the lower social classes and were often freedmen. Fewer than 19 percent of *officinatores* were slaves.[80] There was much money to be made for both the upper and lower classes through the large imperial building projects,[81] and cooperation between them ensured that both benefited from the building activity in the city during flush times.

A number of *redemptores*, such as Q. Haterius Evagogus and Ti. Claudius Onesimus mentioned earlier, are known to have been officials of the *collegium fabrum tignariorum*, which was an organization composed largely of builders. Unlike the medieval guilds, which had political power and strict control over their crafts, the *collegia* were primarily social organizations during the first three centuries of the empire. In Rome, the various *collegia* of craftsmen were not under the direct control of the state, although one of the advantages of membership included some exemptions from public services as encouragement to practice crafts that would benefit the state.[82] The *collegium* of the *fabri tignarii* was the largest of the craft guilds attested in Rome, and its organization dates from the late Augustan period.[83] A *faber tignarius* was strictly speaking a carpenter, but numerous inscriptions indicate that membership was not limited to woodworkers, and the *collegium fabrum tignariorum* seemed to have been open to builders of all kinds. Inscriptions listing the members of the *collegium* in Rome in the late second century reveal that the membership was as high as 1,330.[84]

Membership in the *collegium fabrum tignariorum* required entry fees and dues and was therefore a show of some financial success. Of the known officers of the *collegium*, many were freedmen and a number of them were also *Augustales*, an honorary priesthood that required a certain amount of public munificence from the holder.[85] These were not simply laborers but, rather, men of some means who were intent on raising their status within the community. The fact that Onesimus advertised himself as a contractor of imperial works suggests that this fact in itself conferred some prestige. J. D. L. Pearse suggests that the individual members of the *collegium fabrum tignariorum* may well have been a primary source of contractors for public works, but he is careful to point out that if this were the case, there is no evidence to suggest that the contracts were acquired through the *collegium*. The success of the individuals in their business dealings may have been related to their activities in the *collegium*, but it was not dependent on it.[86] DeLaine has recently argued for a somewhat more active role for the *collegium* in organizing labor for large imperial projects.[87] Along with kinship and *clientela*, the *collegia* undoubtedly formed another cog in the machinery of the building industry and provided a means of advancement and a sense of achievement for the lower segments of society.

For a contractor interested in advancing in the profession, contracts of *locatio conductio operis*, in which he took direct responsibility for his work and the building site, would have provided him the most control and flexibility. The use of such a contract, however, raises the question of his responsibility for the soundness of the structure. The vaulting techniques discussed in this study were often used to ensure the stability of the building. For large projects, an architect usually was involved. So, who then decided when and how to use the various vaulting techniques intended to ensure stability – the builder or the architect? The architect designed the building, but the builder put the pieces in place. In the *Digest of Justinian*, the jurists dealing with private buildings are particularly concerned with the legal obligations of both the client and the contractor in situations of building failure, but the obligations of the architect do not seem to be of great concern.[88] The *redemptor* was only responsible for building failure until the final inspection. If the building failed a week or even a year after the inspection, it was the fault of the person in charge of the *probatio* who was an agent of the patron,[89] possibly the architect. The architect was typically hired in a different manner from the contractor. He was paid an honorarium for supplying technical skill and advice rather than manual labor. He was, therefore, not directly responsible for the structure, though he could be sued for deliberate fraud, which included gross incompetence.[90] The details of many difficult structural problems were probably worked out onsite with both architect and builder contributing their own expertise to the discussion. In the end, we must assume that the most innovative buildings were the result of the collaboration between a visionary patron and a creative architect working with experienced builders.

By the beginning of the fourth century A.D., the organization of the building industry in Rome had changed, largely in response to the political instability and economic crisis during the mid-third century. When Diocletian took over and established the tetrarchy, he reorganized the provinces and instituted tax reform. Italy for the first time was included in the taxed areas. A land tax (*iugatio*) was introduced, and the landowners paid their assessed taxes in kind, depending on what they could produce.[91] The new tax system became a means of requisitioning building materials for the state. The evidence for the chronology of the implementation of the new tax scheme in the various areas of the empire is incomplete, but Italy seems to have been divided into provinces by A.D. 294.[92] Within this scheme, the supply of building material to Rome was the responsibility of the *praefectus urbi*, whose jurisdiction included areas within a one-hundred-mile radius of the city (Map 2, p. 13).[93]

The new taxation system had a great effect on construction in Rome by increasing state control of materials and labor. B. Ward-Perkins traces the effects that the change had on public munificence in Italy and points out that the social mobility of the freedmen, who had used the building trade as a means of advancement earlier, was much reduced in the fourth century.[94] Many of the *redemptores* of earlier times were replaced with a system in which labor for building projects was requisitioned by the state as means of collecting taxes or through the *collegia*.[95] Under the new system, the *collegia*, which had once been voluntary societies that conferred some prestige on its members, became an obligatory requirement for workers of a particular skill.[96] Both membership and the movements of the members were strictly controlled. Similarly, some professions were made hereditary so that there was limited flexibility in adapting one's work to one's innate skills.[97] The incentive to use the building trade as a means of social and economic mobility was thus removed as was the sense of pride that came in membership of the various *collegia* of craftsmen.

THE INNOVATIONS

In the final chapter, I employ a framework based on four criteria that have been used for identifying innovation in agricultural technology: (1) *accumulated knowledge*, (2) *evident need*, (3) *economic possibility*, and (4) *cultural/social/political acceptability*.[98] So, for example, a brief and simple application of these criteria to the early development of concrete vaulting in central Italy yields the following: The development of the arch and the discovery of pozzolana-lime mortar constituted the *accumulated knowledge* necessary for concrete vaulting to develop. The desire to create usable flat terracing at hillside sites of religious sanctuaries in central Italy is an example of *evident need*. The wealth coming into Italy during the second century B.C. from conquests and taxation provided the *economic possibility* for building the increasingly grand sanctuaries. *Cultural acceptability* then developed from the desire to match the architectural accomplishments of conquered territories in the Hellenistic Greek world, in which hillside sanctuaries, such as those at Cos and Lindos, had gained international repute. These four criteria also are applied throughout the following chapters, but in a less systematic manner than in the final chapter.