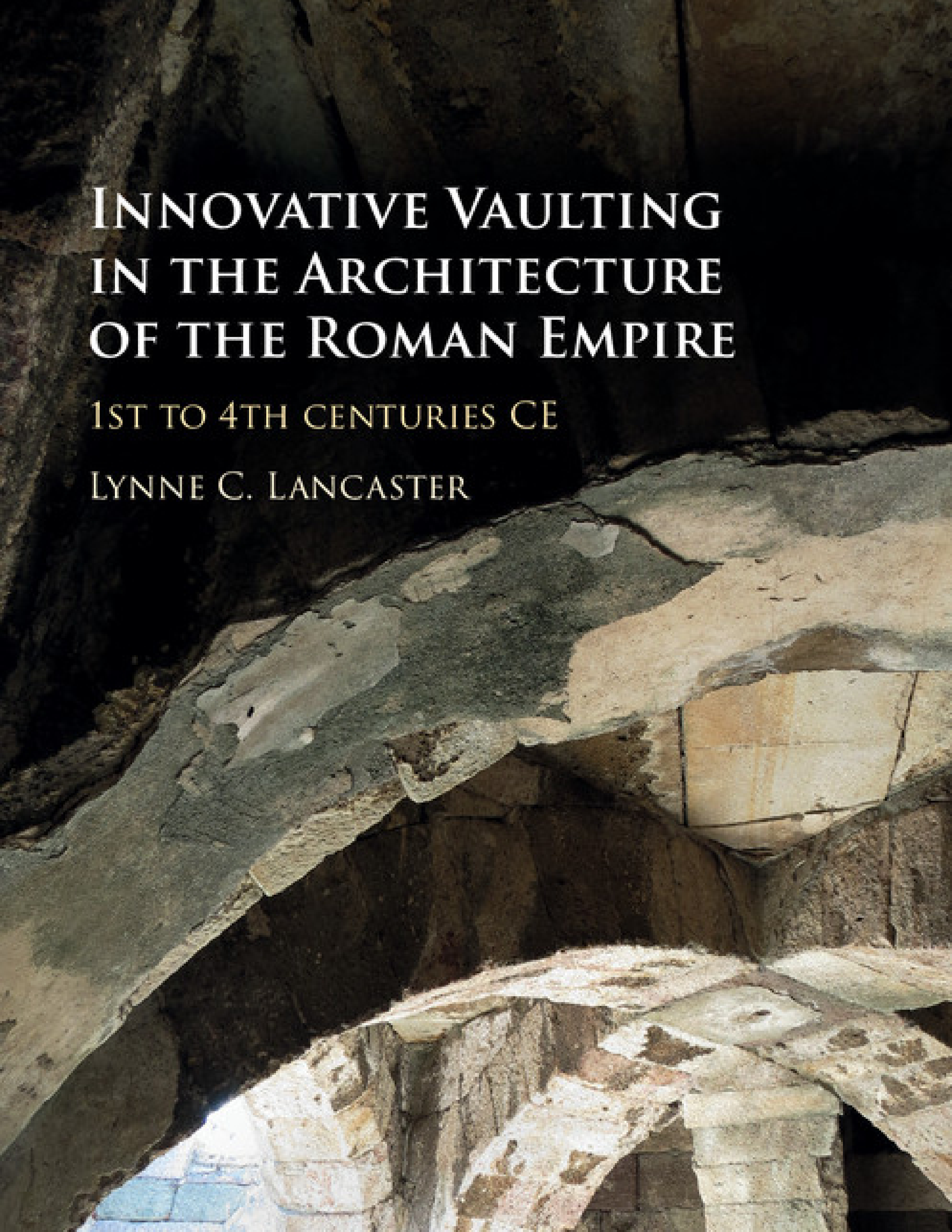
Innovative Vaulting in the Architecture of the Roman Empire

1st to 4th centuries CE

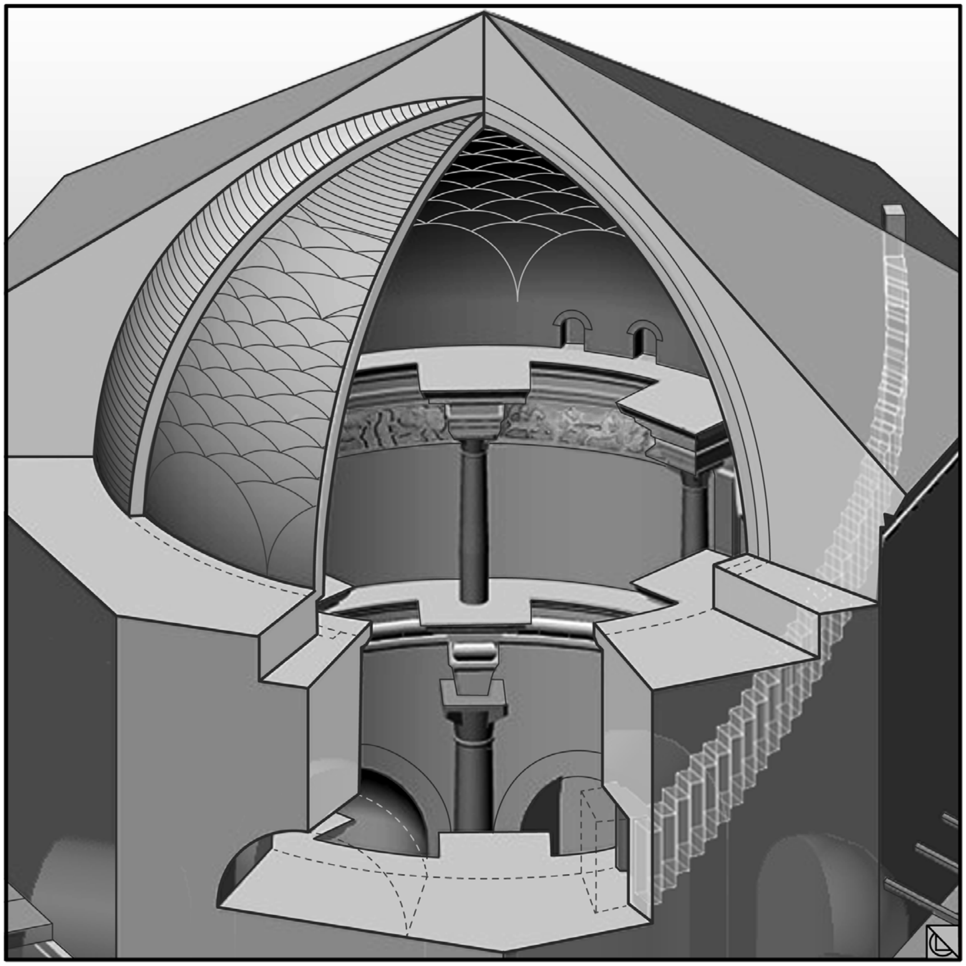
Lynne C. Lancaster



INNOVATIVE VAULTING IN THE ARCHITECTURE OF THE ROMAN EMPIRE

This book studies six vaulting techniques employed in architecture outside of Rome and asks why they were invented where they were and how they were disseminated. Most of the techniques involve terracotta elements in various forms, such as regular flat bricks, hollow voussoirs, vaulting tubes, and armchair voussoirs. Each one is traced geographically via GIS mapping, the results of which are analyzed in relation to chronology, geography, and historical context. The most common building type in which the techniques appear is the bath, demonstrating its importance as a catalyst for technological innovation. This book also explores trade networks, the pottery industry, and military movements in relation to building construction, revealing how architectural innovation was influenced by wide-ranging cultural factors, many of which stemmed from local influences rather than imperial intervention.

Lynne C. Lancaster is a professor in The Department of Classics and World Religions at Ohio University. She has been both a Fellow at the American Academy in Rome (FAAR 2002) and a resident at the British School at Rome. Her first book, *Concrete Vaulted Construction in Imperial Rome* (Cambridge University Press, 2005), won the Wiseman Book Prize from the Archaeological Institute of America in 2007.



Frontispiece. Drawing of the dome of the Mausoleum of Diocletian at Split (detail of Figure 60).

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1st to 4th Centuries CE

LYNNE C. LANCASTER
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In memory of my grandmother, Bertha Seigler (1898–1985),
who was determined for me to see the world

Sherlock Holmes to Dr. Watson:
"It is a capital mistake to theorize before one has data.
Insensibly one begins to twist facts to suit theories,
instead of theories to suit facts."
– Sir Arthur Conan Doyle, *A Scandal in Bohemia* (1891)

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PREFACE

This book is a sequel to my earlier book, *Concrete Vaulted Construction in Imperial Rome: Innovations in Context* (Cambridge 2005). After completing that project, I knew that I wanted to continue the study of vaulted construction outside of Rome and Italy, but was not sure what form that study would take. Fortunately, in 2005 John Oleson invited me to contribute a chapter on Roman engineering and construction for the *Oxford Handbook of Engineering and Technology in the Classical World* (Oxford 2008). While preparing this chapter, I discovered that there were great lapses in the synthesis of building techniques outside of Rome. Of the many regional studies, few considered the differences and similarities between various areas of the Roman Empire or how and why a technique occurred in some places and not others. There was a clear need to put this material into a broader context. I completed the book chapter knowing that there were many questions still to be answered and that some things that I wrote could change in the future. Yet that project provided me with the framework for this book, and the contributions of the other authors to that volume helped shape my approach.

During the fall of 2005, I was in Rome working at the American Academy library in a cluster of carrels alongside Brian Rose, Fikret Yegül, and Philip Stinson, all of whom were shocked that I had not yet visited Turkey. They offered much encouragement and advice on where to go and what to see. So the following summer, my husband and I rented a car and made a month-long tour of the major sites of Asia Minor; it was one of the more life-changing trips I have made. Fikret and Phil kindly met us and accompanied us on visits to Sardis and Aphrodisias, respectively.

In spite of the magnificent architecture I encountered on that trip, I began to realize that what interested me were the differences between regions, rather than the unique aspects of any one of them. Therefore I began to make lists of examples of vaulting techniques that I encountered in both my readings and travels. During my stay in Rome in 2008, I met Stefan Zink, then a graduate student at the University of Pennsylvania, who showed me a GIS project that he was working on with Lothar Haselberger. After I shared with him an overview of my own project, he quickly convinced me that GIS would be the perfect tool for the "lists" I had made. The use of GIS added yet another dimension to the project and provided a much-needed organization tool.

Another seminal event that affected the approach taken in this book was a workshop on port networks in March 2008 held at the British School at Rome and organized by Simon Keay and Timmy Gambin, which I attended as a spectator rather than presenter. There I came into contact with a group of scholars working on ports, navigation, connectivity, and trade in terracotta products. Exposure to the conversations and the issues that came up made me realize that some of the same questions could be directed at material relating to building techniques. The papers from the conference have now been published in *Rome, Portus, and the Mediterranean* (London 2012).

This project required a great deal of traveling throughout the territories of the Roman Empire: In the past decade it took me to Turkey, Egypt, Tunisia, Greece, France, Croatia, and Britain. After that first trip to Turkey in 2006, I was fortunate to have been invited as a visiting professor on a TUBITAK grant to the University of Mersin in the fall of 2007. My host, Professor Emel Erten, steadfastly took care of me for my three-week stay and provided excellent companionship as she introduced me to the sites of Cilicia. In addition to a few other visits to Turkey, in 2013 I made a second "grand tour" of the major sites in Asia Minor. Nick Cahill generously hosted me at Sardis, and Alexander Solicek and Allison McDavid gave up precious time before their season began to accompany me around Aphrodisias. At Ephesus, I am grateful to Sabine Ladstaetter, director of the Austrian excavations there, for arranging access to both Terrace Houses and for her hospitality over dinner at the Austrian Institute. Dennis Murphy helped me find the elusive and beautiful site of Rhodiapolis, which took two trips and ultimately a GPS device. Margaret Miles at the American School in Athens was also very helpful during one of my trips to Greece in search of information on Hadrian's Aqueduct at Athens.

I am indebted to Sean O'Neill for his guidance in setting up our Egypt trip in December 2010, which ended only a few weeks before the revolution broke out. Traveling outside of a group tour in Egypt is challenging to say the least, but thanks to contacts Sean provided, everything went as smoothly as possible given the circumstances. I am also grateful to Sebastian Enceina at the Karanis Archives at the Kelsey Museum, who helped me find all the information that I needed on the early University of Michigan excavations in the Fayum; that help was invaluable because I discovered on my trip there that most of the structures have long been reburied under the sands.

The study of hollow voussoirs (Chapter 6) required visits to numerous museum collections in Britain. I was a graduate student at Oxford in the 1990s, but I was not remotely interested in the archaeology of Roman Britain at that point, so when I returned in the summer of 2011, I was entering a new world. I found the scholars and museum curators incredibly generous in sharing their expertise and access to materials. Above all Ian Betts at the Museum of London has been my mentor in all things regarding bricks and tiles of Roman Britain. I also received invaluable help and guidance from James Kenny at the Chichester District Museum and Ernest Black of the Relief-Patterned Tile Research Group. Roger Tomlin at Wolfson College Oxford kindly advised me on the interpretations of tile graffiti. The following museum curators were also very generous with their time and access to collections: Anooshka Rawden at Chichester District Museum, Robert Symmons at Fishbourne, Juliet Nye at the Littlehampton Museum, Susan Fox at the Museum of Bath, Paul Roberts and Richard Hobbs at the British Museum, and Emma O'Connor at Barbican House at Lewes.

For the study of the materials used in *opus caementicium* (Chapter 2) I benefited enormously from my collaboration with a group of geologists in Rome: Fabrizio Marra, Guido Ventura, and Gianluca Sottili. Without their expertise, the rock analyses and provenance identifications would not have been possible. They also made excellent travel companions for our day trips into the countryside around Rome and on a particularly memorable trip in which we spent a few days living in the Vesuvius Observatory on the flanks of the volcano as we collected our samples. During that trip, we were also fortunate to have Ferdinando De Simone act as *cicerone* for our excursions to the quarries and sites of his home territory along the north flanks of Vesuvius.

Another memorable research trip was one to Argos, Greece, with Carla Amici, Paolo Vitti, and Paolo's (very patient) wife Isabel, who was content to let the three of us obsess about the bricks and walls of the amazing cult complex there. It was a rare pleasure and privilege to be able to immerse myself in the minutia of construction with other enthusiastic experts. Carla and Paolo were also tremendously supportive of this project with both their time and ideas.

Occasionally during one's travels, happy coincidences occur. That was the case during a visit to Croatia in 2012, when I went into a bookstore near the Mausoleum of Diocletian in Split and asked if they had any publications by Goran Nikšić, an architect whose works I had read. The shop owner responded, "No, but his wife works next door if you want to talk to her." So I found her and she took us to his office. My husband and I then spent all that day and part of the next in Goran's company as he took us to every nook and cranny of ancient Split and, most importantly, to climb up to the inner cornice of the dome of the mausoleum from where I took the photograph in Figure 57.

I owe great thanks to a number of people who devoted their time and energy to reading and commenting on various chapters of this manuscript: Carla Amici (Ch. 1, 3, 7), Jim Anderson (Ch. 1-9), Ian Betts (Ch. 6), Barbara Burrell (Ch. 3, 4), Stefano Camporeale (Ch. 5, 7), Tom Carpenter (Ch. 1-9), Tim Clerbaut (Ch. 7), Lothar Haselberger (Ch. 1–7), John Ochsendorf (Ch. 1, 8), John Oleson (Ch. 1, 2), Jane Shepherd (Ch. 5, 7), Paolo Vitti (Ch. 1, 3, 4), Mandy White (Ch. 1, 2), and Greg Woolf (Ch. 7). I am grateful to all of them for saving me from embarrassing mistakes and generally making the book better and more user friendly. They bear no responsibility for the opinions expressed.

This project would not have been possible without help from numerous scholars with various types of expertise. Hazel Dodge, who taught my course on Roman architecture at Oxford, was an early influence who drilled into my head that architecture outside of Rome was important, even when I was completely focused on the capital itself. Many other people shared with me their expertise and research, both published and unpublished: Martin Bachmann, Hansgeorg Bankel, Jacopo Bonetto, Kim Bowes, Evelyne Bukowiecki, Macarena Bustamonte, Manfred Deiler, Janet DeLaine, Richard Etlin, Michalis Kappas, Nikolaos Karydis, Amanda Kelly, Sandra Lucore, Marcello Mogetta, Bob Meyer, Naomi Norman, Jennifer Palinka, Ted Peña, Nigel Pollard, Ursula Quatember, Margareta Steinby, Lea Stirling, David Stone, Hilke Thür, Monica Trümper, Barbara Tsakirgis, Pier Luigi Tucci, Roger Ulrich, Massimo Vitti, Susan Walker, Peter Warry, John Wilkes, Andrew Wilson, Roger Wilson, Mark Wilson Jones, and Ulrike Wulf-Rheidt. Colleagues who generously allowed me to reproduce their photographs include William Aylward, Jane Biers, Stefano Camporeale, Miles Lewis, Sandra Lucore, Goran Nikšić, Evan Scherer, Miriam Shadis, Phil Stinson, and Ulrike Wulf-Rheidt. I am indebted to Glenn Bugh, Barbara Burrell, Steve Hays, and Bill Owens for helping with Greek translations. I am ever grateful to John Ochsendorf at MIT, who has guided me through the process of thrust line analysis over the years. Special thanks are due to Jim Anderson, Lothar Haselberger, John Oleson, Bob Ousterhout, and Fikret Yegül for their steadfast support of this project over the years.

Finishing the drawings for this book during the summer of 2014 was a Herculean task. Ultimately I could not do it alone in the time I had, and I am extremely grateful to two undergraduate students, Theo Peck-Suzuki (Brown University) and Kendall Markley (Ohio University), for helping me out with their skills in Adobe Illustrator and for their willingness to take on some of the more tedious aspects of the creation process. I also appreciate all the help I received from the staff of the Inter Library Loan Department at Alden Library at Ohio University and from my two main research libraries at the University of Cincinnati and at the American Academy in Rome.

My sabbatical year in Rome in 2007–08 was generously funded by the National Science Foundation. The Department of Classics and World Religions and the College of Arts and Sciences at Ohio University also provided funding for my many travels. I am especially grateful to my editor at Cambridge University Press, Beatrice Rehl, for her unwavering belief in and support of both this project and my first book when opinions of reviewers wavered. Most importantly my husband, Tom Carpenter, made it all possible with his companionship during all of our travels, as well as his unflagging support and encouragement, especially after the economic crisis of 2008 when research funding at all levels disappeared. We ultimately decided that an unpaid leave of absence from university duties during the 2011–12 academic year was necessary for this project to be completed in a timely manner. He also took the time to read the entire manuscript (at least twice) while completing his own book project.

Finally, I dedicate this book to my grandmother, Bertha Seigler (1898–1985), who was determined that I would see the world and made sure that I did. She lived long enough to see me set off for my first overseas trip as a study abroad student during the summer of 1985.

1

INTRODUCTION

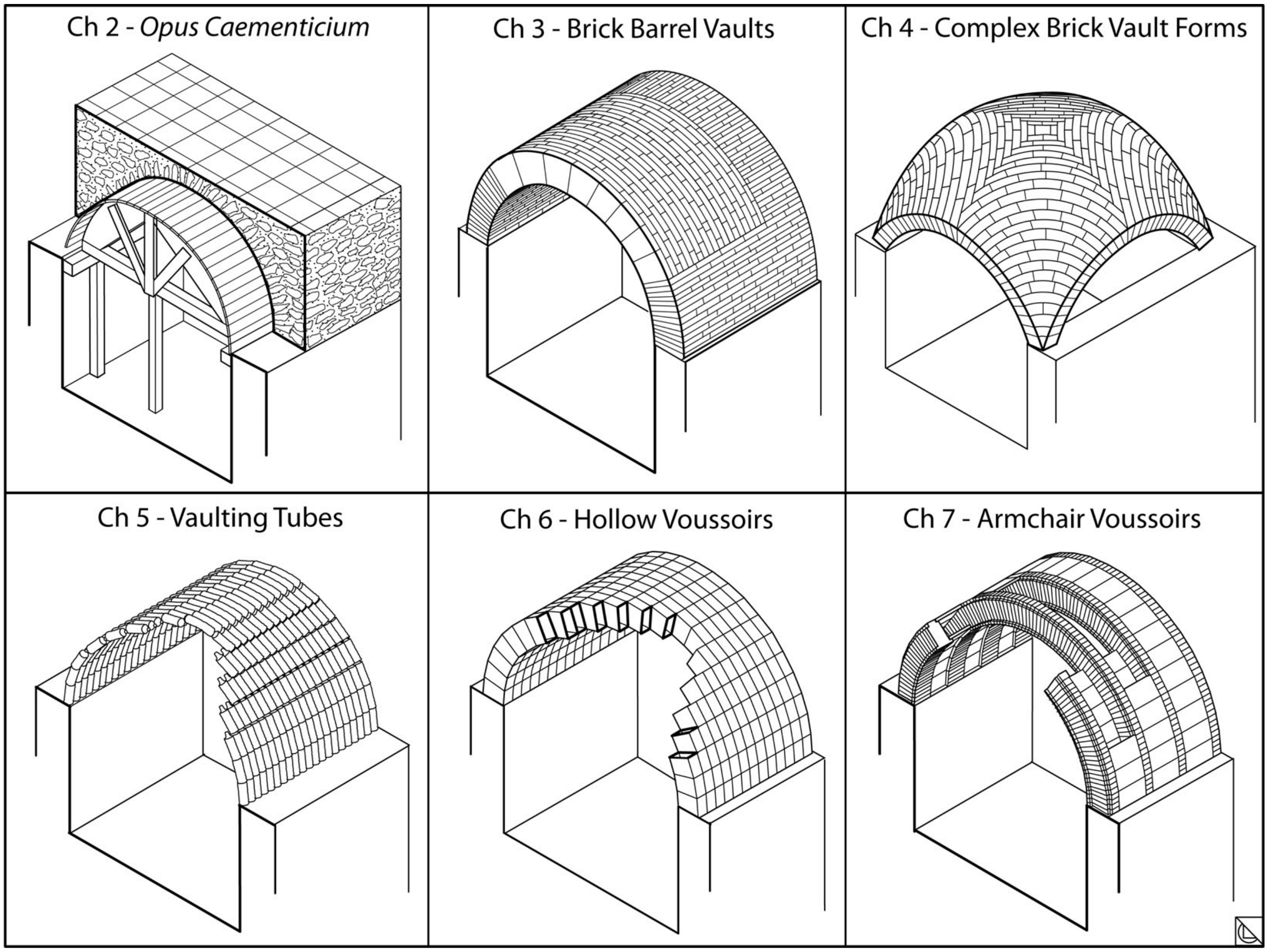
The impressive vaulted structures of ancient Rome have been seen as the embodiment of the power of the Roman Empire, whereas the vaulted structures scattered throughout the provinces of that empire have attracted less attention. They have typically been regarded as smaller, lesser imitations of the greatness exemplified by those in Rome itself. Even the term – provincial architecture – brings with it connotations of inferiority, subservience, and mediocrity. This mindset that privileges the center over the periphery shaped the way in which Roman architecture, particularly construction technology, was studied during the twentieth century. From a sociopolitical perspective, the architecture of the Roman provinces has often been presented as a result of the local patrons and builders adopting forms and methods developed in the imperial capital as a means of emulating those in power; however, as more recent scholarship emphasizes, the reality is much more complex.

My focus is on the originality of the vaulting techniques used in structures throughout the Roman Empire. The techniques examined in this study were often unknown in the capital, and their development was the result of a web of factors that differed from region to region. Certainly the imperial system was the loom on which the web was woven, but the innovative results were the inspiration of individuals who were responding to local conditions – social connections, economic pressures, and political realities. By examining a specific set of vaulting techniques, I try to unravel some of the threads that affected their creation and dissemination.

HOW TO USE THIS BOOK

The book is organized so it can be used by both general readers and specialists. Each chapter provides a brief introduction to the major issues and a conclusion that includes an overview and assessment of the material discussed. 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. Chapters 2–7 each begins with a drawing of the technique being studied, which is then followed by a distribution map of all the locations where that technique occurs. Each distribution map has a corresponding

Catalogs (WebCat.) and color figures (WebFig.) can be downloaded at www.cambridge.org/vaulting

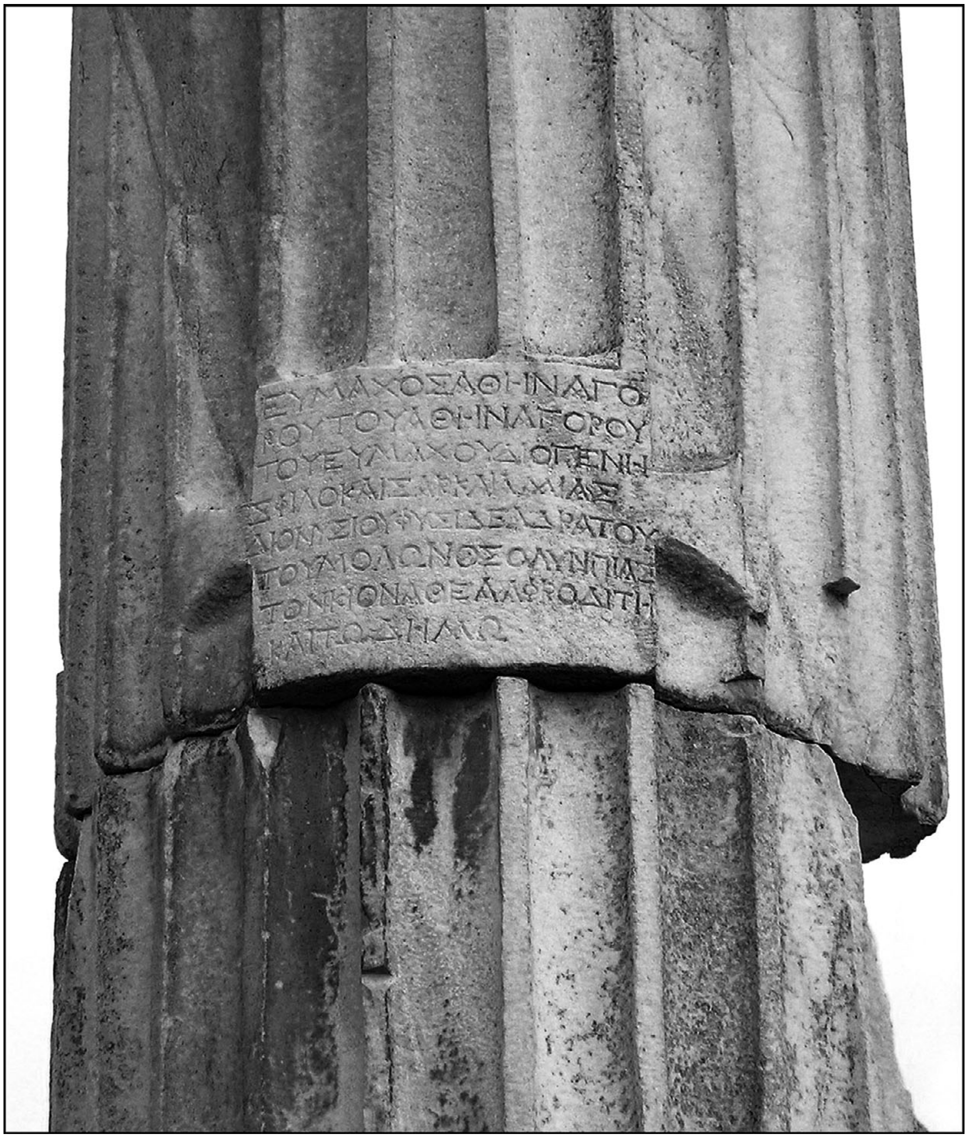


1. Illustrations of the six techniques under examination.

database of all the examples, noted as a Web Catalog, which can be downloaded from the Cambridge University Press website (www.cambridge.org/vaulting). Some of the Excel files making up the Web Catalogs contain more than one sheet, in which case the sheets are labeled A, B, C, etc. So, "WebCat. 5-B" refers to sheet B within the Excel file called WebCat. 5. In the text, I only discuss examples of a technique that illustrate the particular points I make. For those who want to pursue the subject further, details and bibliographical references for each entry on the distribution maps are included in the Web Catalogs. A separate bibliography for the references in the databases is provided as a downloadable pdf file. Supplemental color illustrations, Web Figures, can be downloaded as pdf files and are designated in the text as WebFig. 1, WebFig. 2, and so on.

GOALS AND INTENTIONS

The study is organized around a group of innovative vaulting techniques chosen because they facilitated the building process, improved the structural behavior of the building, or improved the function of the building in a manner that benefited the user (Fig. 1). In some cases, they provided more than one of these advantages, and the reasons for their use could change over time. Each of the techniques



2. Column of the Temple of Aphrodite, Aphrodisias, with dedication inscription by Eumachus Diogenes and his wife Ammias Olympias (late first century BCE to early first century CE) (photo: Philip Stinson).

tells a story of its own and provides insight into broader issues, such as the relationship between various types of technologies (construction, agriculture, pottery), the effect of trade networks and military movements on technology transfer, and the role of the imperial administration in promulgating technological change. I do not deal with innovative new vault forms unless the shape was inherently generated by the construction technique being studied. Moreover, the study is *not* intended as a survey of vaulted construction throughout the Roman Empire; rather, it uses a defined set of vaulting techniques as a means of looking at larger questions of technological development.

My intention is to document this group of vaulting techniques in order to identify cultural factors that influenced why they developed when and where they did and to determine why they spread to particular areas and not to others. In other words, I use the chosen vaulting techniques as vehicles for tracing technology transfer over time, and I relate them to changing political and economic conditions. By focusing on the individual building elements and materials of vaulted structures, I place the emphasis on process rather than product – I examine the factors leading to the constructional choices made by builders and their patrons and how the choices differed between regions and over time. The geographical scope of the project is defined by where the techniques were used. The chronological scope is from the beginning of the imperial period under Augustus to the reign of Constantine, when his embrace of Christianity brought about a shift in the power structure that affected the allocation of resources to building projects. Some of the techniques continue beyond the fourth century, but I intend to deal with this later material (fourth to sixth centuries CE) in a subsequent work that will also revisit late antique vaulting in Rome and Italy after the capital moved to Constantinople.

METHOD AND APPROACH

I have sometimes been asked, "What is your method – inductive or deductive?" Thinking about this question, I realized that I oscillate between the two modes of reasoning. The beginnings of this project were inductive in that I started with the specifics and worked toward a general explanation by collecting as many examples of each technique as I could find and then examining the data using a spreadsheet and a GIS map to help form hypotheses that could explain the phenomena represented by the data. I then shifted to the deductive approach and tested these hypotheses by searching for additional material (historical, epigraphical, archaeological) that could support or reject the hypotheses. During the twentieth century, deductive approaches (i.e., starting with a general hypothesis) often led to the neglect of relevant evidence that could have challenged the original hypothesis. I realize that the results presented here may well change when new information comes to light, but I hope that at a minimum this study serves to reframe the questions being asked about the role of building technology in the provinces and to provide a body of evidence that can be enhanced in the future to refine the questions even further.

As a framework for developing the hypotheses, I adopted a definition of technological development cited by K. Greene, which identifies three phases: (1) *invention/discovery*, (2) *innovation*, and (3) *diffusion/technology transfer*.[1] Invention is defined as the act of implementing an original idea in a new device or process, whereas innovation is the process by which the invention is brought into use.[2] Pinpointing an invention is difficult in the ancient world, and it may represent the eureka moment or chance discovery of an otherwise unidentified craftsperson. The innovation phase is often more informative because it reveals more about the broader context. This phase can also be understood in terms of four factors: (1) *accumulated knowledge*, (2) *evident need*, (3) *economic ability*, and (4) *social acceptability*.[3] The third phase of technological development includes diffusion, the process by which an innovation is spread within society, and with it technology transfer – the spread of skills, knowledge, and processes from one area to another. Both provide insight into the motivating social, economic, and political forces within society.

I found that these three phases frequently coincided quite closely with my assembled data. For example, the idea for a technique might result in an invention quite early, but the innovation that allowed it to be used on a wider scale occurred much later and in a different place when the four influencing factors cited earlier came together to create the appropriate context. Then once the innovation was spread to other areas of the empire (diffusion), it often changed in small ways to respond to different conditions. Another useful concept emphasized by Greene is the *technology shelf*, which refers to the range of technological choices, both materials and processes, available in a particular time and place to respond to specific circumstances.[4] The establishment of the Roman Empire dramatically increased the technological choices available to patrons, architects, and builders, so when we see a particular vaulting technique, its use usually represents only one of many options. The technology shelf reminds us that technological determinism rarely explains the whole picture; human choice was also at work. Choice was affected by a myriad of factors (personal alliances, economic constraints, and social pressures) that may not have even been clear to the person making the choice, much less to the present-day archaeologist trying to interpret the fragmentary evidence. The technology shelf thus helps define the context within which the individuals involved in a project were working. As we see, the shelf was broad, but its contents varied throughout the empire.

This project is dependent on nineteenth- and twentieth-century studies of construction in the Roman provinces, particularly by A. Choisy (fl. 1870–1900) and J. B. Ward-Perkins (fl. 1950–80),[5] as well as on more recent work by scholars such as J. P. Adam, H. Dodge, and F. Yegül.[6] In addition, I refer to numerous studies that focus on individual techniques in particular regions. The creation of the databases on which this study is based would not have been possible without the careful observations and documentation published by other scholars. Many of these more detailed studies on individual techniques occurred during the 1980s and 1990s: for example, G. Brodribb on hollow voussoirs (1983, 1987); S. Storz (1994) and R. J. A. Wilson (1992) on vaulting tubes; A. Bouet (1999), M. Fincker (1986), and A. Torrecilla Aznar (1999) on armchair voussoirs. Likewise, excavation and survey work at many sites has yielded and continues to produce new information. Thus, since the time of Choisy and Ward-Perkins, the nature of the evidence has changed dramatically, and much of it has not yet been synthesized.

The approach to ancient technology has shifted greatly since the major works on building construction were written. The study of ancient technology has typically been linked to studies of the economy. During the twentieth century the dominant theory was the primitivist view, most notably that of M. I. Finley, whereby ancient technology was seen as stagnant due to the reliance on slave labor and the inherent cultural disdain for its practical applications.[7] Building construction in particular was not seen as relevant. In fact, H. Hodges's *Technology in the Ancient World* (1970) and J. G. Landels' *Engineering in the Ancient World* (1978)[8] did not include building technology at all. Recent approaches to the Roman economy advocate for a more complex view in which technological advances play a much greater role than acknowledged previously,[9] and the strictly positivistic approach to ancient construction technology as a how-to manual is moving to a more holistic approach that looks at the building industry as a branch of a larger economic entity. J. DeLaine's work, *The Baths of Caracalla: A Study in the Design, Construction, and Economics of Large-Scale Building Projects in Imperial Rome* (1997), has influenced attitudes by examining the building process step by step and presenting a methodology for quantifying the level of economic stimulus provided by the construction of such a large project.[10] The renewed interest in building technology among archaeologists is exemplified by a series of five international conferences, "Arqueología de la construcción" (Mérida 2007, Siena 2008, Paris 2009, Padua 2012, Oxford 2015).[11]

More generally, the changes in attitudes toward the study of cultural dynamics in the provinces can be seen in the debates over the definition of

Romanization, a term coined in the early twentieth century. The British scholar F. Haverfield put forth the original view of Romanization during the time of British imperialism.[12] It referred to the spread of Roman culture to conquered peoples and implied a one-sided influence – the values of the conquerors imposed on the conquered. The ancient passage most often cited to support this view is Tacitus's description of the contributions of his father-in-law Agricola as the governor of Britannia:

> By private encouragement he [Agricola] set about persuading men who were scattered, uncultured and thus easily aroused to warfare, to become peaceable and accustomed to pleasures offered by leisure. In public he assisted them to build temples, fora, and residences, praising those who were quick to follow his advice and criticizing those who were slow. A competition for honor thus took the place of compulsion . . . and by stages they were led on to the more acceptable vices, public arcades, bath houses and the sophistication of banquets. In their inexperience they took this for *humanitas* when in fact it was part of their slavery.[13]

At a time when ancient texts were prioritized over archaeological evidence, the scholarly ethos during the early twentieth century easily incorporated Tacitus's view of imperialism. A century later, in the early twenty-first century, scholars see Rome's relationship with its provinces in a different light. With the loss of many European colonial possessions after World War II, a postcolonial approach developed that focused on reassessing the historical narratives put forth under colonial rule. Modern imperialist nations had often invoked the Roman Empire as a model for their own land grabs, stressing a view of Romanization as a force for good in spreading civilization. In the 1990s M. Millet proposed an alternative to Haverfield's concept of Romanization that emphasized the importance of material culture as a corrective to the literary tradition.[14] He advocated an approach that avoided the pro-imperialist assumptions that accompanied the traditional view of the empire. Instead, he used a model in which the process was not driven from the central power of Rome as implied by Tacitus, but instead was more spontaneous, with the elite taking a primary role in provincial governing and in adopting Roman values and the lower classes then emulating their own elite.[15] This model also came under criticism for continuing the top-down approach, and others sought to focus on the non-elites, particularly the indigenous culture made up of the less powerful. These debates sometimes led to an "either-or" mentality. For the present study, postcolonial revisionist approaches can provide a useful corrective to traditional assumptions, but one has to avoid losing perspective and, as S. Alcock put it, "throwing the baby out with the bath water" in denying any top-down model.[16] That the Roman Empire had a radical effect on the areas it conquered cannot be denied, but there are many subnarratives with native inventors as protagonists. Together these overlapping stories bring us closer to understanding the complexity of the whole.[17]

The major work in English on architecture and construction in the provinces remains J. B. Ward-Perkins's handbook, *Roman Imperial Architecture* (originally published in 1970). The basic thesis that guides the book was formed before attitudes toward the provinces had moved away from the imperialist approach that focused on the capital. For example, Ward-Perkins never mentioned many of the innovative vaulting techniques discussed in the present study, even when he was clearly aware of their existence. They simply did not fit into his narrative, which emphasized the emulation of Italian architecture in the provinces. Ward-Perkins was of a generation interested in looking for similarities between provincial architecture and that of Italy to illustrate the role that provincial builders played in Romanization, an approach that was part of the zeitgeist of early to mid-twentieth-century Europe when many European nations still maintained colonial ties.[18] Nevertheless, in spite of the similarity of architectural forms, if one scratches the surface to see how the structures were put together, one finds that the provincial builders were not simply "borrowing," "superimposing," and "importing" existing ideas, but were actively "inventing," "innovating," and "creating" new ways of building. Recent research dealing with construction in the provinces has advanced tremendously, but it is dispersed in a wide range of publications and languages that have yet to be synthesized into any type of overview comparable to Ward-Perkins's handbook. The present study does not purport to provide such a much-needed handbook because it deals with only a very limited set of data, but it is intended as a first step toward integrating the new material into a more coherent narrative.

PROVINCIAL ADMINISTRATION AND THE BUILDING INDUSTRY

The development of the most innovative vaulting in Rome occurred largely in imperial building projects, but this was not the case in the provinces. Rarely can any of the projects discussed in this book be directly related to imperial funding or sponsorship, though local authorities may well have availed themselves of technical advice or expertise supplied by the emperor. To put the vaulting techniques discussed in the following chapters into the appropriate context, I first examine the evidence for how the projects, particularly public ones, were funded and executed.

One necessary criterion for technological innovation is the ability to finance projects, and this ability is particularly important for building technology. The vaulting techniques studied here occurred in both private and public structures. The source of funding for the former is clear, but the funding for public works, typically the largest of the monuments investigated, had greater variety. Some emperors provided funds for public buildings throughout the empire, but this was more the exception than the rule. In G. Fagan's study of the inscriptional evidence from the Latin West for benefactions of public baths, only 9.7 percent belonged to emperors and 13.3 percent to imperial officials. The vast majority of public bath construction in the West was funded by the municipal authorities (49.5 percent) or private benefactors (27.5 percent).[19] In the Greek East, studies by both P. Barresi and S. Schorndorfer reveal a similar pattern.[20] Emperors were inclined to leave the sponsorship of the most visible projects to private benefactors or municipal officials, which in turn provided these local residents a means of promoting their standing within their communities. However, there were other means for an emperor to provide aid such as donating material (e.g., marble), providing specialist expertise, and waiving taxes.

The private benefactors tended to be the male members of the elite, many of whom acted as municipal magistrates or priests, but benefactions were also made by prominent women, such as Plancia Magna at Perge and Julia Memmia at Bulla Regia.[21] Public structures could also be funded piecemeal with a combination of municipal funds and private benefactions. Examples of gifts to pay for particular parts of buildings are common, as can be seen in the "adopt a column" approach at the Temple of Zeus at Euromus and at the Temple of Aphrodite at Aphrodisias, where each column bears an inscribed dedication by its sponsor (Fig. 2).[22] Pliny the Younger describes a similar situation at Nicea (modern Iznik) where individuals funded different parts of the theater.[23] For the project that Dio Chrysostom (late first century to the early second century CE) sponsored at Prusa (modern Bursa) in Bithynia, he even claims to have measured the site and made personal trips into the mountains for some related task (for procuring materials?).[24] Most patrons were probably not so directly involved, but the more prominent ones could have been in contact with the governor of the province or with officials in Rome itself, so that access to technical expertise outside the local environs was possible. The nature of the technology shelf varied from one region to the next, but the imperial system guaranteed a fairly wide range of possibilities for both public and private structures throughout the empire.

When the cities themselves were the major funders, income came mainly from three sources: taxation on local trade, income from public lands, and the *summa honoriaria* (payment for office) of local magistrates and priests. This last source demands some explanation because it overlaps with donations from private benefactors and provides some insight into how urbanization under the empire affected the spread of technology. A typical Roman colony was governed by a municipal council (*decuriones*); membership criteria specified a minimum age, property qualifications, and election to a magistracy. Obligations of office included the *summa honoraria*, which consisted of a minimum set amount that the elected official was expected to spend on the community from his personal wealth. Similar expectations held for elected priesthoods. Clearly those who were elected had to be able to afford the *summa honoraria*. They were often the same people who sponsored public building, and it is sometimes difficult to know from the wording of a dedicatory inscription if the benefactor was donating funds as part of his official obligation or from personal munificence.[25]

In places like Gaul and Britain where urbanism came largely with the Roman conquest, the organization of a provincial administration provided new avenues of funding for developing cities. Augustus and his successors instituted reforms, such as linking Roman citizenship to provincial magistracies and introducing newly developed priesthoods for the imperial cult, that provided ways of funneling funds via the *summae honorariae* to newly established colonies and to the *civitatis* (independent political communities) that replaced the pre-Roman *oppida* (native settlements). The system had the advantage of providing for the growth of urbanization and with it the elite class to fund it.[26] That one finds the earliest major public building projects in Gaul in the colonies (often settled by veterans), such as Narbonne, Arles, Orange, Vienne, Lyon, and Fréjus, is not surprising. As we see later, urbanization was accompanied by the building of baths, which in turn promoted innovations in vaulting technology for bath buildings. Similar funding strategies existed in the Greek East, as indicated by a letter to Trajan from Pliny the Younger when he was governor of Bithynia in the early second century BCE. He complained that the city of Claudiopolis (modern Bolu) was using the funds from the new magistracies authorized by the emperor to construct a bath building (about which he had some doubts).[27] Thus, in both the East and West, members of the municipal elite were responsible for much of the public building in one way or another.

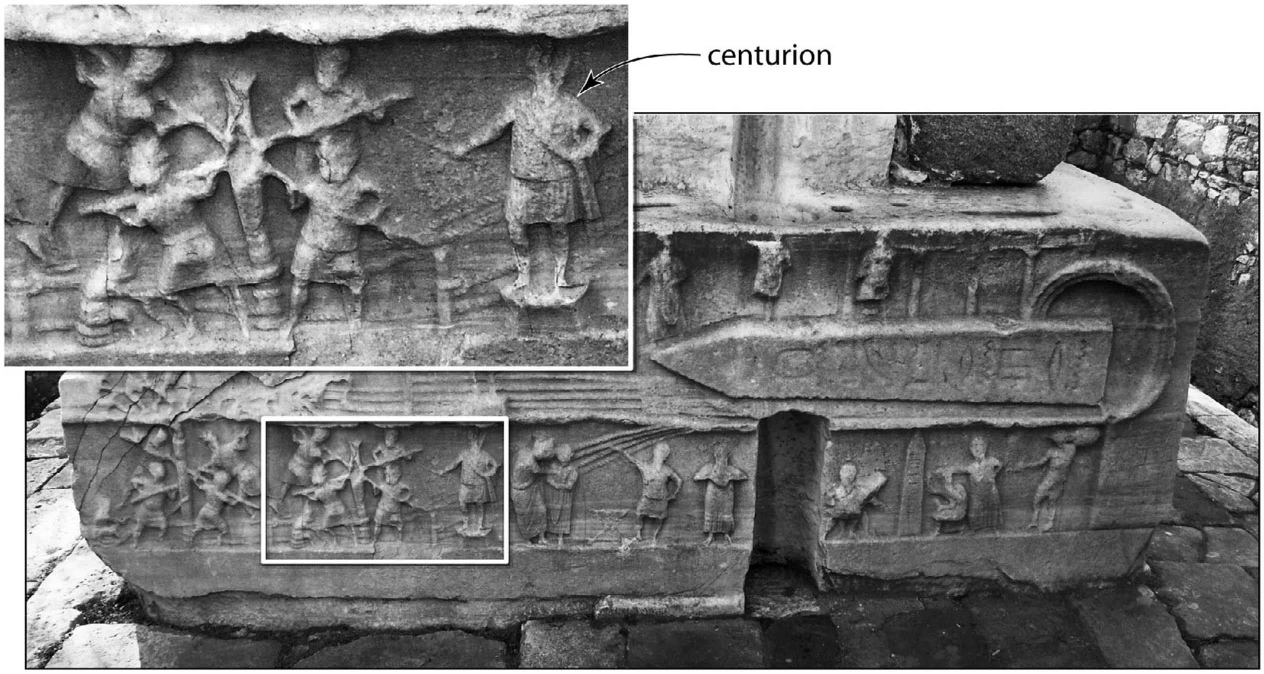
Even though most public building projects were not imperially funded, they were often still subject to imperial oversight.[28] The third-century jurist, Aemilius Macer, noted that any structures for public assembly such as theaters, amphitheaters, and circuses must have imperial approval, regardless of who funded them. Moreover, any new building constructed with public funds also had to be approved by the emperor, as did one sponsored by a private citizen if it was intended to "outdo another citizen."[29] Such approval was presumably to help rein in competitive building and euergetism so that cities did not fall into debt. It is not clear in what period such strict oversight was instituted, but even by the time of Trajan we hear that an official was appointed to oversee the free cities of Achaea.[30] Pliny gives some evidence for his own oversight of the theater at Nicea and the bath at Claudiopolis, both mentioned earlier. Concerned about possible overspending and bad engineering, Pliny requested that Trajan send out an architect to inspect the projects, to which Trajan gave his famous rejoinder: "You cannot lack architects: every province has skilled men trained for this work. It is a mistake to think they can be sent out more quickly from Rome when they usually come to us from Greece."[31]

An example of why there was such concern for oversight can be seen in the case of Herodes Atticus who, as *corrector* of the free cities of Asia in 134/5 CE,[32] requested three million drachmas from Hadrian to provide the city of Alexandria Troas with a new aqueduct. Notably, Alexandria Troas was not one of the free cities he was overseeing, but rather was a Roman colony. When the project ran four million drachmas over budget, the officials in other cities in Asia complained to Hadrian that "it was a scandal that the tribute received from five hundred cities should be spent on the fountain of one city." In response Hadrian wrote to Herodes's father, Atticus, who immediately offered to cover the extra cost and save his son (and the family) from embarrassment.[33] In the East where competition between cities was rampant, this phenomenon may have been more problematic than in the West.

What seems clear from the inscriptional and textual evidence is that even when the imperial administration was not the source of funding for public building in the provinces, the vast imperial infrastructure of roads, harbors, safe navigational routes, and technical expertise offered advantages that expanded the technology shelf from which builders could choose. One such advantage was the availability of military personnel for construction projects requiring special knowledge of surveying, water control, complex machinery, and advanced structural design. The military served as a repository of expertise, with retired veterans, active soldiers, and specialists at hand.[34] In another of Pliny's letters to Trajan he requested an architect or *librator* (a surveyor specializing in leveling) to be sent to Nicomedia (modern Izmit) to help determine the feasibility of cutting a channel to connect Lake Sapanca to the Sea of Marmora. Trajan advised him to apply to Calpernius Macer, who was the legate in charge of three legions in Moesia Inferior in 112 CE.[35] Trajan was clearly referring Pliny to the ample supply of military experts available in a nearby province. Similarly, Ulpian, a third-century CE jurist, notes that a provincial governor should use *ministeria militaria* to evaluate and assist in construction projects.[36] Direct military intervention, however, is rarely recorded for specific civilian projects, except in cases of fortification walls and occasionally aqueduct projects.[37]

The well-known example of Nonius Datus at the aqueduct of Saldae (modern Béjaïa) in Mauretania in 152 CE demonstrates the use of both a military expert and a military labor force. Nonius Datus, who calls himself a *librator*, had been sent out from the Legio III Augusta at Lambaesis to Saldae to lay out an aqueduct tunnel, where he appointed a group of sailors and a group of Alpine troops to start digging the tunnel from opposite ends. Later when the two groups missed each other in the middle, Nonius was called back from retirement to help remedy the situation.[38] A much later example of the military engaging in a civilian project comes from the base of the Obelisk of Theodosius I (390 CE) in Istanbul, which shows a centurion directing the moving of the obelisk (Fig. 3).

Although the military may have supplied expertise at times, the primary source of labor for public projects in the provinces was through private contractors. Plutarch describes the following process: "Cities, as we know, when they give public notice of intent to let contracts for the building of temples or colossal statues, listen to the proposals of craftsmen



3. Base of the Obelisk of Theodosius I, Istanbul (390 CE). Scene of the transport of the obelisk. Detail shows soldiers (with baldrics) turning a capstan while a centurion wearing a baldric with sword and holding a centurion staff (*vitis*) directs the work.

(τεχνιτων, *techniton*) competing for the contract (ἐργολαβίας, *ergolabias*) and bringing in their estimates and models, and then choose the man who will do the same work with the least expense and better than the others and more quickly."[39] A city council would typically appoint a curator of works (Latin *curator operum*; Greek ἐπιμελητής, *epimelitis*), who would be responsible for purchasing the site and issuing the contracts, though as seen in an inscription from Miletus discussed later, an architect could also issue contracts.[40]

Under Roman law, building contracts were typically a type called *locatio conductio operis* (lease and hire). The patron (*locator*) let out a job to be completed by the builder (*conductor*). The contract included a final inspection (*probatio*) and an agreed-on price (*merces*). The builder took on responsibility for the site until the final inspection of the work,[41] which released him of responsibility. Similar types of contracts governing lease and hire existed under Greek law, called μίσθωσις (*misthosis*), which included building contracts. Whether local law or Roman law prevailed in the provinces was not strictly defined. Generally the "personality principle" was used whereby disputes between two non-Roman citizens would be settled using local law and those between two Roman citizens using Roman law. For disputes between those of mixed citizenship some ambiguity existed, and other factors were considered, such as the amount of money involved and the status of the disputing parties, with the governor of the province stepping in when large sums and important people were involved.[42] Once Roman citizenship was extended throughout the empire under Caracalla, these distinctions theoretically would be mute. In contracts of both *locatio conductio operis* and *misthosis*, detailed specifications could accompany the agreement, along with deadlines for completion and penalties for delay, so even in cases where Roman law did not prevail, the ramifications of breaking a contract should have been similar.

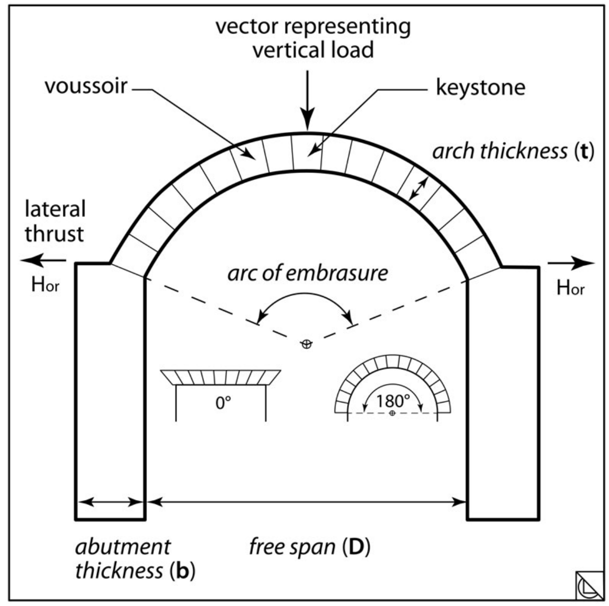
A glimpse into the workings of a public project in Asia Minor and the various people involved is provided by an inscription found on the upper tier of the theater at Miletus (WebFig. 1).[43] It records questions posed to the oracle of Apollo at Didyma by workers at the theater and provides the god's answer.

> Οἱ οἰκοδόμοι οἱ περὶ Ε[. . .]ΝΙ[. . .]
> Ἐπίγονον, **ἐργολάβοι** τοῦ μέρουσ τοῦ
> θεάτρου, οὗ **ἐργεπιστατεῖ** ὁ προφήτ[ης]
> [θε]ọῦ Οὐλπιανὸς ἥρως, **ἐργοδοτεῖ** ὁ **ἀ[ρ]-**
> **[χι]τέκτων** Μηνόφιλος, τὰ εἰλήμα[τα]
> [κ]αὶ τὰ τετ[ρ]άετα κατὰ τῶν κειόνων
> περιειλῶσιν καὶ ἐνέγκουσ[ιν ἢ] ἄλλην ἐρ-
> γοδοσίαν σκέπτωνται; / Θεὸς ἔχρησε·
> Ἐμπεράμοις πινυταῖς δωμήσεσιν εὐτεχνίαις τε
> εὐπαλάμου φωτός τε ὑποθημοσύναισι φερίστου
> χρῆσθαι σύμφορόν ἐστι λιταζομένοις θυσίαισι
> Πάλλαδα Τριτογένειαν ἰδ' ἄλκιμον Ἡρακλ[ῆα].

> Shall E . . . Epigonas, and the builders, contractors for the part of the theater of which the superintendent is the Prophet of the God [a priesthood], the late Ulpianus and for which the architect Menophilos gives out the work, undertake the placing of the arches and vaulting and carry it through or should they consider another task? The god replied, "It is advantageous to you, praying to Pallas Tritogeneia and to valiant Heracles with sacrifices, to make use of the building skills and counsels of an able and excellent man."[44]

For this project there was a supervisor (ἐργεπιστάτης (*ergepistatis*)), Ulpianus, who apparently was in charge of one section of the theater reconstruction, but had died during construction of the project. The theater had various phases of reconstruction during the second century, so he could have been in charge of one phase of construction as opposed to being one of multiple supervisors simultaneously overseeing different parts of the theater. The architect, Menophilos, was the one (ἐργοδότης (*ergodotis*)) who gave out the contracts. The god's response suggests that the difficulty of the work was a concern. The implication is that the builders took the job on contract (because they are called ἐργολάβοι (*ergolaboi*)) and were finding the job more difficult than they had anticipated and were therefore debating whether to default. The god is circumspect in his response: He does not name the expert as the architect Menophilos, but instead leaves the judgment of the "able and excellent man" for the builders themselves to decide.[45] The gods to whom they should sacrifice were Athena and Heracles, both of whom would presumably help them get on with the job. The nature of the work appears to have involved vaulting, so I return to examine this inscription further in Chapter 4.

At the end of the third century, provincial administration underwent a profound change when Diocletian instituted the Tetrarchy and reorganized the provinces. Along with the reorganization came shifts in political power and social relationships among the elite, who were most often the patrons of the buildings, both public and private, in which the most innovative construction occurred. To understand the distribution patterns of the vaulting techniques examined, a basic understanding of these sociopolitical changes is necessary. Under the new organization, the number of provinces almost doubled, thereby reducing the size of the area for which each governor was responsible. In addition, the military responsibilities of the governors were gradually removed, leaving them to focus on tax collection and judicial responsibilities. The provinces were then grouped into twelve dioceses, each responsible to an equestrian *vicarius*. The new double-tier governmental hierarchy, coupled with greater power for the military, vastly increased the bureaucratic structure. One result was that the political power of the senatorial class, entry into which had long been based on birth and landholdings, was shifted to the equestrian class; its members now held many of the most important offices in the imperial bureaucracy, giving them the opportunity to accumulate vast landholdings. Constantine advanced the trend by expanding the senatorial order once he created his new capital at Constantinople.[46] This change in administration had a great effect on the cities, with those acting as centers for the provincial governor or for the *vicarius* of the diocese experiencing urban growth, such as Trier, Milan, Ephesus, and Mérida, and others undergoing contraction and abandonment. In the less urbanized areas of the western empire that did not host the imperial entourage of bureaucrats, the wealthy often invested in rural villas as private displays of self-expression, thus creating a renaissance of villa construction and renovation during the fourth century.[47] The new governing structure of the empire during Late Antiquity created new opportunities for social mobility, and this change is reflected in the distribution patterns of some of the vaulting techniques examined.



4. Drawing of arch showing terms used in text.

BUILDING VAULTS: STRUCTURE AND CONSTRUCTION

In a previous work, *Concrete Vaulted Construction in Imperial Rome* (2005), I dealt extensively with some of the basics of vault construction and structural behavior, and I do not want to repeat myself here. However, a review of some of the fundamentals will be useful in helping the reader appreciate the importance of the innovations in the following chapters because understanding the difference in the way vaults were built outside of Rome requires some different analytic tools.

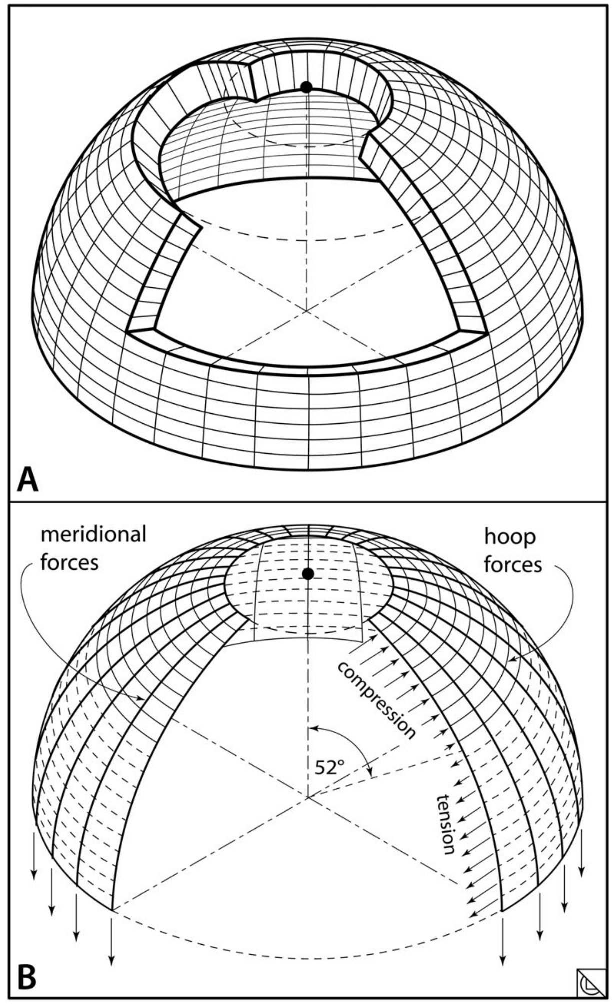
Structural Behavior

The basic principle behind an arch is that the wedge-shaped stones (voussoirs) transfer the weight of the arch and whatever it supports across the radiating joints between the stones to either side of the opening below (Fig. 4). Once the keystone is put into place, "locking" the voussoirs into a structural system, the arch is activated, and that transferred load begins to push down and out on the abutments. The arch is an optimal form for stone and brick, both of which are very strong in compression but weak in tension, because the forces are all in compression as the voussoirs press against each other. The stability of an arch is governed by three variables: the *arc of embrasure* (also called the *angle of embrace*), the *arch thickness* (t), and the *free span* (D) (Fig. 4). The stability of the overall structure is also affected by two other variables: *abutment thickness* and *abutment height*. Knowledge of the way in which these five variables interrelate provides a useful tool for analyzing vaults and understanding why the builders made the choices they did in particular situations.

The arc of embrasure is the angle created by the two lines extending from the center point of the circle defining the arc to the springing point of each side of the arch. It ranges from 0° for a flat arch to 180° for a full semicircular arch. By manipulating the arc of embrasure, the arch thickness, and the free span, a builder can control the behavior of the vault. For example, a shallow vault (low arc of embrasure) can have a smaller arch thickness than a full semicircular vault with the same free span, but it will also impose greater lateral thrusts on the abutments. Thus, the thinner, shallower vault may require wider abutments than the thicker, semicircular vault. Any additional weight (surcharge) added above the vault itself, such as mortared rubble fill, also affects the relationship of the vault to its abutment and ultimately the stability of the whole structure. The relationship of the arch to its abutments is examined further in Chapter 8.

Fortunately, theoretical relationships between the three factors governing arches have been established. For a semicircular arch with a full 180° arc of embrasure, the theoretical maximum ratio of arch thickness to free span (t:D) is 1:17.6.[48] So, a semicircular arch that has a free span that is more than 17.6 times the arch thickness cannot support itself and will collapse. For example, a 30 cm thick semicircular arch would have a theoretical maximum span of just over 5.25 m. In reality, an arch or barrel vault would fail before reaching this maximum due to external factors such as imperfections in the joint surfaces or local crushing of the material in compression. However, this theoretical maximum is useful because it can be easily applied to test for the stability of a semicircular arch or barrel vault with a defined thickness. If the span of a semicircular arch surpasses the maximum allowable t:D ratio, it can be stabilized by adding surcharge above the haunches, which effectively reduces the arc of embrasure, thereby allowing the maximum span to increase.

A dome acts somewhat differently from an arch or barrel vault because its double curvature creates unique behavioral characteristics that allow it to span much farther than other types of vaults and to employ different building methods. A dome built of voussoirs



5. A: Drawing of dome built of radial voussoirs. B: Diagram showing stress patterns in an uncracked hemispherical dome.

is essentially like a series of self-supporting horizontal rings stacked one on top of the other (Fig. 5A). One can think of each course in the dome as two horizontal arches placed end to end to form a circle. In the same way that the keystone locks the voussoirs of an arch together, the final stone in each horizontal course of a dome locks the blocks of that course into place; the converging joints form horizontal rings in compression, each of which supports itself. Unlike an arch, which requires centering until the keystone is put into place, the voussoir dome can be built with temporary centering that can be shifted as each course is put in place; it can even be built without any centering if mortar is used to keep the units in place. The technique of using radially laid bricks to build hemispherical domes without centering is still used today in some places around the world.[49]

Unlike a simple barrel vault, which has internal forces acting along a single axis, a dome has internal forces occurring in both directions of curvature: meridional forces (along the longitudinal lines, acting as arches) and circumferential hoop forces (along the latitudinal lines). The meridional forces are similar to those in barrel vaults and act mainly in compression. The circumferential hoop forces represent the unique aspect of dome behavior because some can act in tension. Structural analyses of a hemispherical dome with an arc of embrasure of 180° show that the meridional and hoop forces are both in compression at the crown, but that the hoop forces can change from compression to tension in the haunches. In a theoretical hemispherical dome with a thickness approaching zero, the point of change from compression to tension occurs at about 52° from the crown, with the tensile forces increasing toward the base (Fig. 5B).[50] In a real dome this angle will vary depending on its arch thickness and arc of embrasure. As with an arch, a lower arc of embrasure allows for a greater span, but it also generates greater lateral thrust on the abutment.

Many domes eventually develop cracks in the lower portions when the material is no longer able to resist the tensile hoop forces. If the cracks were to go right up to the crown, the dome would be acting like a series of independent arches propped against each other. Nevertheless, as long as the abutments do not spread, the dome would remain standing. In reality, the cracks are typically limited to the haunches of the dome, so that the uncracked portion at the crown can still develop compressive hoop forces that increase its stability over that of the dome with cracks extending to the crown. Because most domes eventually develop cracks at the haunches, engineers at MIT calculated the limits of stability for a partially cracked dome in which no hoop tension was allowed to develop in the haunches. They found that the theoretical limit for the ratio of arch thickness to free span (t:D) for such a dome is 1:49,[51] which is well over twice the allowable ratio for barrel vaults (1:17.6). So, a hemispherical dome can span over twice as far as a semicircular arch of the same thickness.

Material Properties

One myth regarding the *opus caementicium* vaults of central Italy is that ancient pozzolanic mortar (i.e., hydraulic mortar made with reactive volcanic ash) was so strong that it was resistant to the tensile stresses that can cause cracking. These vaults have often been described as "monolithic" and compared to a lid that simply sits atop a pot and exerts no lateral pressure. This misconception is relevant for the study of vaults outside of central Italy because it has affected the way in which these structures have been evaluated. The idea of the monolithic concrete vault was expressed by A. Choisy in 1873 and has often been repeated. However, a quarter-century later he modified his assertion to make a more subtle distinction between the theoretical possibility of Roman pozzolanic concrete having the strength to act monolithically as opposed to the observable fact that cracks indeed occurred.[52] Nevertheless, the idea of the monolithic Roman concrete vault was repeated by major writers on the subject during the twentieth century, including M. E. Blake, J. B. Ward-Perkins, and J.-P. Adam.[53] That hydraulic mortar is stronger and more resistant to tensile stresses than simple lime mortar is true, but to assume that it can resist the substantial stresses it could undergo in large vaults is misleading. Moreover, this misconception led to the belief that vaults in Rome exerted no outward pressure on their abutments, whereas provincial vaults did because they did not have the advantage of volcanic ash ("pozzolana"), a topic explored further in Chapter 2.

In fact, even the highest quality concrete vaults in Rome exerted some lateral thrust because concrete, both ancient and modern, is subjected to a phenomenon called *creep* – the slow deformation over time due to the pull of gravity.[54] The mortar gains its strength slowly, so creep is greatest during the first few years. This elasticity in the material means that it will always be exerting some horizontal force on the abutments even if it has not yet cracked. The degree of pressure will change over time as the vault deforms and the concrete becomes stronger. The builders in Rome were clearly aware that they could not rely on the strength of the concrete alone to ensure stability, and by the time of Augustus they began to develop various ingenious ways of countering the outward thrust of their vaults. Vaults made with *opus caementicium* of simple lime mortar also exhibit creep, but it could be countered by using a lower proportion of mortar to stone and laying the stones radially so that they acted as voussoirs to distribute the loads more evenly through the structure.

One of the more sophisticated methods devised by the Roman builders to reduce lateral thrusts was to control the weight of the materials making up the vault. They understood that by making the crown of the vault lighter and the haunches heavier they could reduce the effect of gravity. The top of the vault is horizontal so the lighter it is, the less lateral thrust it generates, whereas the curve of the vault at the haunches is nearly vertical so the added weight there helps counter the lateral thrusts by "pushing" them downward onto the abutments. This was one of the techniques used in the Pantheon dome.[55] It developed in central Italy where the builders could use the locally available lightweight volcanic stones, such as scoria and pumice, in the concrete mixture. Builders outside Italy clearly understood the principle because we find evidence both for the importation of lightweight volcanic stones to nonvolcanic areas and for the use of lightweight sedimentary stones (usually calcareous tufa) in place of volcanic stones.

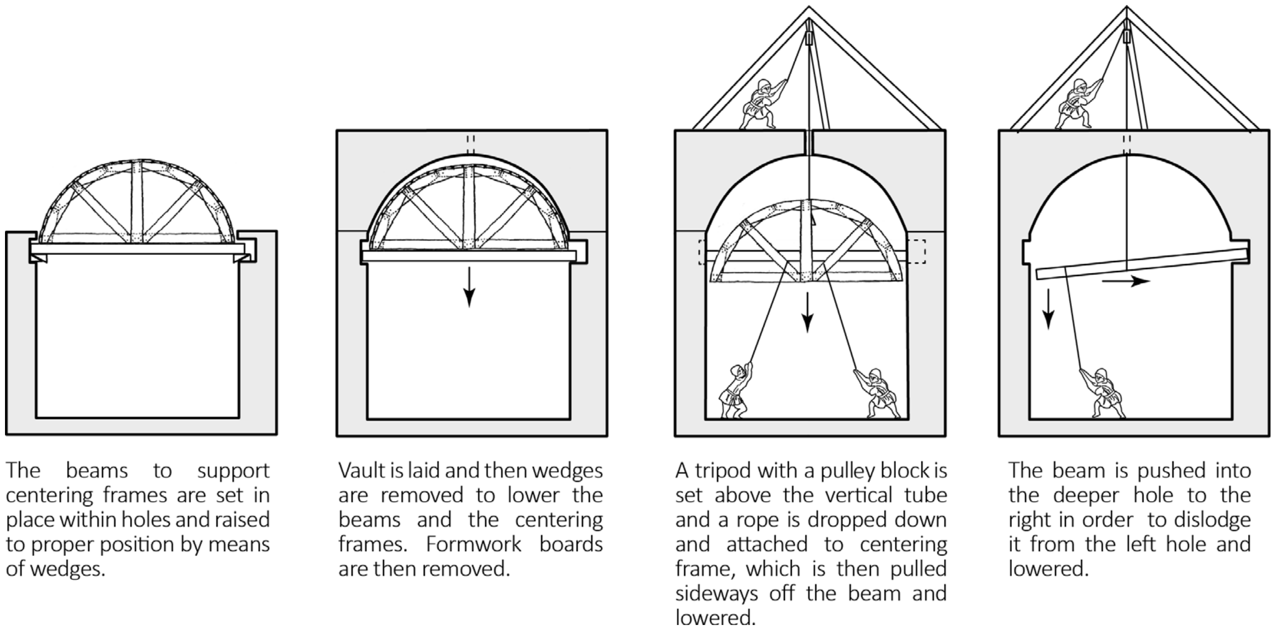
Centering

Most vaults require a temporary wooden structure called *centering*, which provides the curved form and the support for the vault during construction (Fig. 1). On completion, the centering is removed, a process that can be a very complex task in itself. The main clues to the existence of the centering structure are the holes or projecting corbels that are sometimes visible at the base of the vault where wooden beams were supported. If the vault was built using mortar, the impressions of the wooden formwork boards can sometimes be discerned. Carpenters were often the unsung heroes of vaulted construction. Great amounts of wood and labor went into constructing the centering before the actual vault was laid, and then extensive planning and organization were required to remove it without incurring damage to the structure or injury to the workers.[56] Among the innovations that one finds in the vaulting techniques in this study are methods of reducing the amount of wood needed or eliminating the centering altogether. These innovations can be seen in three of the techniques examined: pitched brick, vaulting tubes, and armchair voussoirs.

An example of the creative methods devised to deal with the erection and removal of centering may be found in the remaining vaults of the substructure of the Temple of Trajan at Pergamum (4.0–4.5 m span; 8.5 m floor to crown). These mortared rubble vaults preserve large rectangular beam holes at the impost as well as a series of vertical terracotta tubes at the crown. The tubes are positioned between the beam holes (i.e., not in alignment with them; Fig. 6). K. Nohlen has proposed that the tubes were intended to help lower the centering by using ropes controlled

6. Temple of Trajan, Pergamum (117–136 CE). View of substructure chamber. Arrows indicate vertical tubes in the crown of the vault, which are positioned between the rectangular centering holes visible on the right.

from above, and he participated in a project of experimental archaeology to demonstrate how the system might have worked.[57] I reconstruct his process in Figure 7. Such vertical terracotta tubes are not commonly found in vaults (except when used for drainage or vents),[58] but another example exists in the substructures of the Baths of Vedius at Ephesus where similar tubes occur at the crown of the vault (6.0 m span; 7.0 m floor to crown) built over Latrine A in the substructures. The beam holes on one side are



7. Temple of Trajan, Pergamum (117–136 CE). Author's sketch of the process proposed by K. Nohlen (2009) for using the vertical tubes to manipulate the centering during construction.

taller than those on the other, presumably to aid in the removal process. The excavators suggest a similar use for the tubes as that proposed by Nohlen at Pergamum.[59]

FINAL THOUGHTS

Vaulted construction existed in stone long before the *opus caementicium* vaults of central Italy came into existence by the second century BCE, but the creation of new forms and the increase in their scale are associated with this new medium. As vaulting became more sophisticated in Rome, a second material – brick – was added to the builder's kit. Terracotta had the advantage of being fireproof, a growing concern after the great fire that destroyed large swaths of Rome in 64 CE, and of being easy to fashion into various shapes. Concrete and brick are often credited with the "revolution" of vaulted architecture that began to appear after the fire.[60] As we see later, building elements of terracotta also played a major role in construction technology outside of Rome but often in new and varied ways. The growth of various sectors of terracotta production (transport amphoras, fine ware, and tiles) led to innovations that are never found in the vaulted architecture of the capital itself. In some cases, the innovations occurred even earlier than the "revolution" that occurred in Rome. In fact, most of the innovative techniques in this study used terracotta, thus emphasizing the close relationship that building construction had with the terracotta industry as a whole. Moreover, the vast majority of the structures that employed these techniques were bath buildings. The advanced technology required for heating and waterproofing bath buildings was clearly a driving factor in the development of a number of the techniques examined.

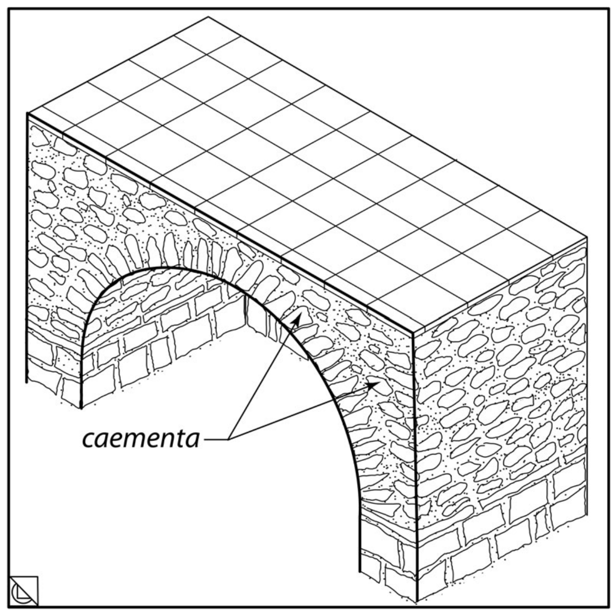
Each of the vaulting techniques tells a different story and touches on different regions of the empire. They act as guides from the small villa baths in

Britain, Iberia, and France; to the growth of cities in North Africa and the Egyptian Fayum; and to the rise of interurban rivalries for prestige in Asia Minor. All of these narratives demonstrate how the human desire for creativity and self-expression manifests itself in architecture, both for the patrons who commissioned the structures and for the architects and builders who constructed them. Yet they also tell the story of imperialism and the way the desires and needs of the imperial administration affected the system in which personal and civic expression took place.

2

OPUS CAEMENTICIUM

The large and intricate vaulting systems in imperial Rome were an outgrowth of the development of *opus caementicium*, or Roman concrete, a vaulting material that was eventually adopted throughout the empire, albeit in different forms. Unlike modern concrete, which consists of small aggregate mixed into mortar that is poured into place, the aggregate in the *opus caementicium* of central Italy was made up of larger stones (10–30 cm), or *caementa*, hand-laid in the mortar (Fig. 8). *Opus caementicium*'s suitability for vaulting depended on two main factors: the high-quality hydraulic lime mortar and the heterogeneous makeup of the mixture, which allowed for the use of *caementa* of different weights in different parts of the structure. This technology developed in central Italy because of the ready availability of a variety of volcanic materials. Volcanic ash ("pozzolana") was added to the lime mortar to give it added strength, which developed more quickly than in simple lime mortar, whereas lightweight stones such as pumice and scoria were used as *caementa* to reduce the weight of the vaults and thus reduce their lateral thrusts on the support walls. These materials were all products of explosive activity from a series of volcanoes along the west coast of Italy. Given that many



8. Drawing of *opus caementicium* vault with radially laid *caementa* along the intrados.

other parts of the Roman Empire did not have a ready supply of such volcanic materials, scholars have often assumed that the builders of vaulted structures outside of central Italy were at a great disadvantage. The intention of this chapter is to explore the degree to which this assumption is true and what alternatives were available in other parts of the empire for

Catalogs (WebCat.) and color figures (WebFig.) can be downloaded at www.cambridge.org/vaulting

employing lightweight *caementa* and creating strong mortars.

The focus of the following discussion is on lime-based mortar because lime is the ingredient that reacts with soluble silica to produce a stronger mortar. However, some of the vaulting techniques discussed in later chapters use gypsum-based mortars, so a brief comment on the difference between lime- and gypsum-based mortars is warranted. Lime is a substance created by the burning of high-calcium rocks such as limestone, travertine, and marble. For example, limestone ($CaCO_3$) must be heated to around 900°C to drive off the carbon dioxide, leaving smaller, less dense stones that are known as quicklime (CaO).[1] To make quicklime into mortar it must first be turned into slaked lime, or calcium hydroxide ($Ca(OH)_2$), by adding water, which results first in the generation of much heat and then the disintegration of the chunks of quicklime into powder. Adding more water creates a putty that can be made into mortar by adding quartz sand (SiO_2) to prevent it from shrinking and cracking once it dries. As the mixture dries it absorbs carbon dioxide from the air and reverts back into a type of artificial limestone ($CaCO_3$), but because it can only absorb the carbon dioxide on the outer surface the inner portions of thick applications never achieve the same degree of strength.[2]

Gypsum, or calcium sulfate dihydrate ($CaSO_4 \cdot 2H_2O$), can also be used to make mortar by heating it to around 300°C to drive off carbon dioxide, thus producing calcium sulfate hemihydrate ($CaSO_4 \cdot 0.5H_2O$) – what is commonly known as Plaster of Paris. If heated to more than 400°C the resultant material will not recombine with water and cannot be used for mortar, so careful control of the heat is necessary. As with lime mortar, it is mixed with inert siliceous sand to prevent shrinkage and cracking. Gypsum mortar has some advantages over lime mortar in that it is much cheaper to process because of its lower calcining temperature and shorter burn time, and it can have a compressive strength up to four times greater than that of lime mortar. It also has a much quicker set time, which can be controlled. The longer the mixing, the quicker the set. This property is beneficial when a quick-setting adhesive is required. However, gypsum deposits are less common than limestone outcrops. The gypsum mortar is also more soluble than lime mortar and can deteriorate in moist conditions.[3] Moreover, it does not have the same chemical potential as lime mortar to combine with high silica additives to produce a hydraulic mortar.

TERMINOLOGY

The Latin term, *opus caementicium*, is usually considered synonymous with *Roman concrete*, and it has sometimes been distinguished from mortared rubble on the basis of its high-quality hydraulic mortar.[4] However, when looking at vaulting outside of Italy such rigid distinctions become problematic because of the variety of materials and methods of use. For example, the mortar has rarely been tested for hydraulic properties so the distinction between hydraulic and nonhydraulic mortar would be difficult to apply as a distinguishing feature. Moreover, the etymology of the term does not suggest that it was originally coined to identify the hard, compact, hydraulic concrete that we typically associate with buildings like the Pantheon. As J. P. Oleson points out,[5] Vitruvius never used the term *opus caementicium* when he introduced the subject of building walls with *caementa*, and he considered all types of lime mortar – employing river sand, *harena fossicia* (quarried sand), *pulvis* (powder) from the Bay of Naples, and crushed terracotta – as potential binders.[6] For him, the defining characteristic was the *caementa*, or rubble. Although he did assume a lime-based mortar, it was not necessarily one that was hydraulic. The term *opus caementicium*, however, does occur on a first-century BCE inscription from Philippi in Greece noting a patron who built a structure of *opus caementicium* in front of a temple. Given the date and location of this structure, it is not likely to have employed volcanic ash mortar. Another inscription, from Lavernae, a small town near Sulmona in the Abruzzi, refers to a wall of *opus caementicium* at the *templum* of Bona Dea.[7] Whether this latter wall employed volcanic ash in its mortar is not known. Thus for the Romans the term apparently denoted the technique employing mortared rubble rather than any specific type of mortar.

One criterion that could be used to distinguish vaults of *opus caementicium* from those of mortared rubble is the setting of the stones in horizontal layers rather than radially, but even this definition can lead to difficulties. For example, the vaults at the Sanctuary of Fortuna at Palestrina (second half of the second century BCE) have the *caementa* (albeit very small ones) along the intrados set radially, as does the dome of the "Temple of Mercury" at Baiae (late first century BCE), yet both are considered prime examples of *opus caementicium* vaults. Ultimately, the modern use and definition of the term have come to reflect the historical focus on the volcanic resources of Rome and central Italy. Given the difficulties in applying the term in a strict sense outside of Italy, in this study I use *opus caementicium* to refer to any construction where the mortar plays a significant structural role in binding stones together, and I often use it interchangeably with *mortared rubble*.

The use of the word "pozzolana" (after the town of Pozzuoli) to describe the volcanic ash added to lime mortar has also affected the modern conception of *opus caementicium*. The association of pozzolana with the Bay of Naples helped shape the idea of a special Roman "monolithic" concrete existing only in central Italy, thereby limiting the vaulting possibilities in the provinces.[8] However, as early as 1958, W. E. MacDonald was puzzled at how pozzolana could be so critical, noting, "The use of pozzolana seems to have been limited to central Italy, and it is difficult to believe in its indispensability in later Roman vaulted buildings because of the preservation and stability of so many provincial examples."[9] The assumption that puzzled MacDonald was that in Italy the builders used pozzolanic (i.e., hydraulic) mortar and in the provinces they did not. This assumption is worth exploring in light of the archaeometric advances made in recent years.

In the following discussion I use the term *hydraulic mortar* instead of *pozzolana mortar* because there are more ways to create hydraulic mortar than simply by adding volcanic ash. Before looking at the alternatives, one must answer some questions. What exactly is pozzolana? How would an ancient builder recognize it? How does it make mortar stronger?

WHAT IS POZZOLANA?

The Italian word *pozzolana* (or sometimes *pozzuolana*) was originally associated with the volcanic ash found around Pozzuoli (ancient Puteoli) that was used to make hydraulic mortar. It was likely inspired by the ancient term used by Pliny the Elder to describe the material, *Puteolanus pulvis* (powder from Puteoli).[10] By the late seventeenth century, English speakers, many of whom had visited the Bay of Naples on the Grand Tour, had adopted the Italian word *pozz(u)olana* to describe any unconsolidated volcanic ash that had properties similar to that found around Pozzuoli. Thus, the word *pozzolana* went from a specific use to a generic one (much as *Xerox* came to mean *photocopy* in American parlance). It is not, in fact, a technical geological term, but rather a term used by modern-day builders and engineers to describe volcanic ash that can be mixed with lime to create hydraulic mortar. In geological terms, the material would be defined as unconsolidated pyroclasts consisting of ash and lapilli of pumice and scoria.

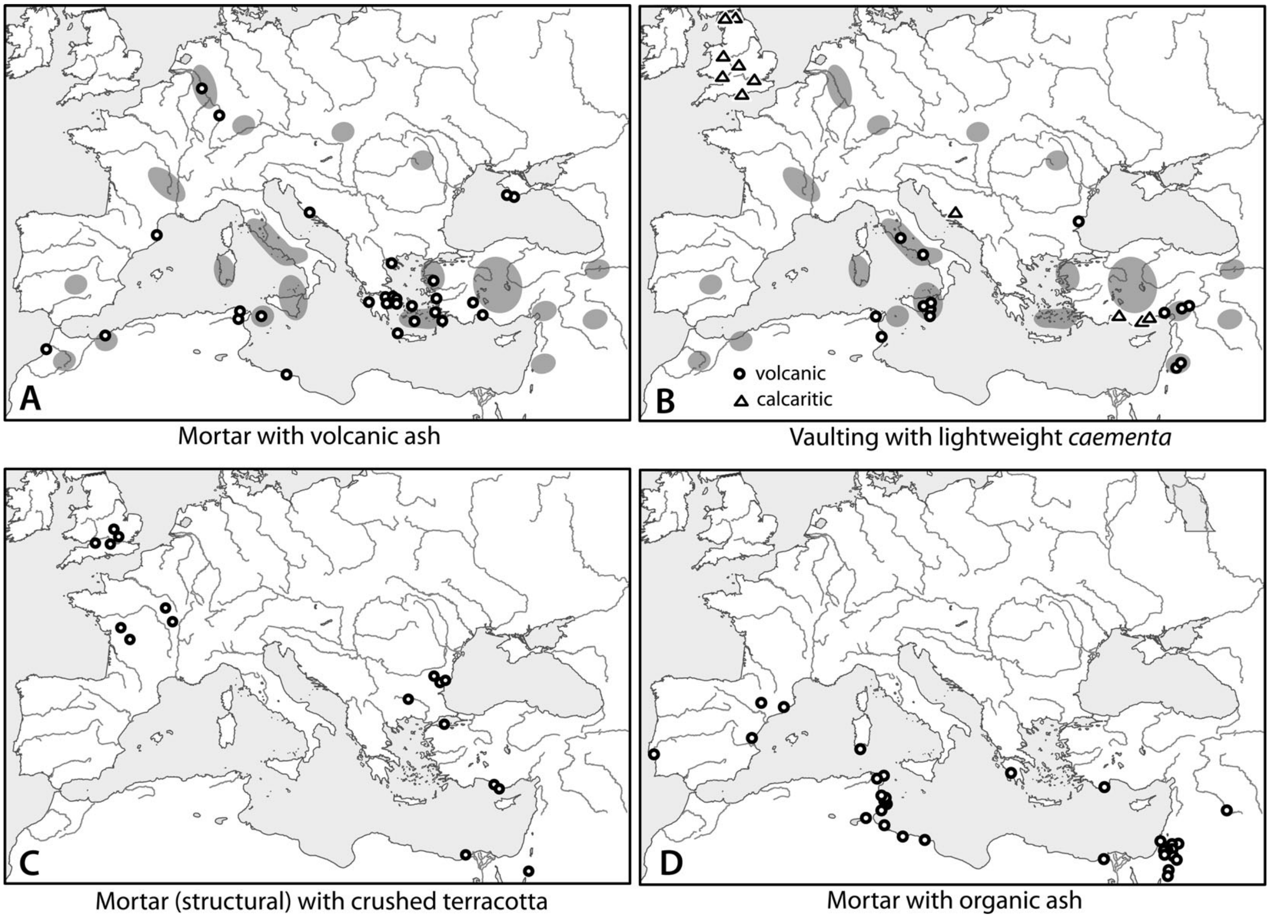
Vitruvius, writing around 25 BCE, is the first author to refer in Latin to the volcanic ash from the Bay of Naples as an ingredient in mortar. He describes it as powder (*pulvis*) found around Baiae and Mount Vesuvius.[11] Only later in the mid-first century CE did Pliny the Elder associate it directly with Puteoli by calling it *Puteolanus pulvis*.[12] Both authors note its ability to create mortar that sets under water when mixed with lime. Strabo, a near contemporary with Vitruvius, describes in Greek the same substance from the Bay of Naples as sand (ἄμμος, *ámmos*) and sand-ash (ἀμμοκονία, *ammokonía*).[13] All three authors associate it with the fiery nature of the surrounding volcanic zone.

The volcanic ash found farther north in the environs of Rome is mentioned for the first time also by Vitruvius, who calls it *harena fossicia*, or quarried sand.[14] Pliny the Elder later uses the same term.[15] They both clearly see it as a material different from the *pulvis* from the Bay of Naples. Vitruvius makes this clear when he notes that given the thermal springs throughout Etruria one might expect to find the same type of *pulvis* as in Campania, but that in fact it does not occur there. However, he does imply that the products of both places are a result of a similar fiery formation process when he makes an analogy between the burnt-out earth (*exusta terra*) in Campania that becomes ash (*cinis*) and the burnt-out material (*excocta materia*) in Etruria that becomes *carbunculus*, which he names as one of the four types of *harena fossicia*, along with black (*nigra*), white (*cana*), and red (*rubra*). In terms of application, he notes that both the *harena fossicia* and the *pulvis* provide advantages in built structures, but he distinguishes *harena fossicia* as appropriate for terrestrial structures because it makes walls that dry quickly and it allows for vaulting (*concamerationes*), whereas the *pulvis* is appropriate for marine structures because the walls get hard under water.[16]

The Roman builders of the early empire clearly thought of *harena fossicia* and *Puteolanus pulvis* as different substances. The modern use of "pozzolana" therefore implies the existence of a single material that did not exist in the minds of the Romans. Hence, some scholars have suggested that one should avoid the term altogether and refer specifically to the appropriate substance according to its Latin designation. Given the imprecise nature of the term, geologists working in Rome have even begun referring to volcanic strata by using capital letters, as in *Pozzolane Rosse* (red pozzolana) and *Pozzolane Nere* (black pozzolana) as a way of emphasizing that it is a proper name rather than a geologically descriptive term.[17]

To further confuse the matter, other modern terms are used to describe volcanic ash outside of Italy. For example, the volcanic ash mined on the island of Santorini is often called *Santorin earth*, and a volcanic ash (in both consolidated and unconsolidated forms) found along the Rhine in Germany is called *trass* or *taras.* Although these materials are not named in ancient sources, the fact that both were employed in mortar mixes indicates that Roman builders outside of the Italy were aware of their beneficial properties when mixed with lime. It is worth noting that the potency of the various volcanic ashes varies with their chemical makeup.[18] A mapping of the volcanic systems shows that volcanic ash was available in many parts of the Roman Empire (Fig. 9A, WebCat. 2-A).

No ancient author mentions the use of volcanic ash with lime mortar outside Italy. Vitruvius even claims that *harena fossicia* is not found on the other side of the Apennines nor in Greece and Asia Minor. He was clearly unaware that a similar type of material was available on various volcanic islands in the Aegean, such as Santorini, Cos, Melos, and Nysiros, of which the latter two are mentioned as sources for volcanic



9. Maps showing extent of the use of various types of mortar and *caementa* (none is intended to be exhaustive). A: Finds of mortar containing volcanic ash (WebCat. 2-A). Gray areas indicate volcanic zones. B: Vaulting employing lightweight *caementa* of calcareous tufa or of volcanic scoria/pumice (WebCat. 2-E). C: Finds of structural mortar with crushed terracotta additive (WebCat. 2-B). D: Finds of mortar containing organic ash (WebCat. 2-C, examples of both wall covering and structural mortar are included).

pumice and sand much earlier by Theophrastus.[19] Vitruvius, Strabo, and even Pliny the Elder were all writing before mortar-based construction became common outside of Italy, so we have no literary confirmation for how or when the knowledge spread.

Because the Latin terms *harena fossicia* and *Puteolanus pulvis* only refer to volcanic materials in central Italy, they are of limited use in the present study; therefore a more generic term is preferable. Moreover, in addition to volcanic ash, other materials possess pozzolanic properties. Hence, to avoid confusion, I follow the scientific terminology and use the term *pozzolan* to describe a category of additives that contain enough soluble silica to react with lime. This category includes volcanic ash, fired clay, and certain organic ashes.[20] Given the associations with Rome and central Italy that the term *pozzolana* has acquired in the literature on classical archaeology, I avoid it in this study and use the more neutral *volcanic ash* to indicate one type of pozzolan.

HOW TO RECOGNIZE VOLCANIC ASH

The physical characteristics of volcanic ash vary according to the volcano and the event that produced it. The color of the ash varies between different volcanoes and between different strata of the same volcano. It can range from very light beige to reddish brown to gray to dark brown to black. In general, volcanic ash consists of airborne deposits of unconsolidated pieces of pyroclasts that can range from dust-sized ash particles to lapilli-sized (1–64 mm) pumices and scoria. So, for example, a section of the light-colored pyroclastic fallout in the Campi Flegrei, where the larger lapilli at the base transition into a very fine ash at the top (Vitruvius's *pulvis* or *cinis*), can be compared to the dark Pozzolane Nere from the Colli Albani district just south of Rome, which consists of variably sized, unsorted scoria fragments (WebFig. 2). This difference is one reason that Vitruvius and Pliny the Elder considered them distinct materials. In cases where paleosoils have accumulated above volcanic fallout, distinguishing between ash and soil can be difficult if the coloring is similar. Vitruvius understood this when he gave two methods for testing *harena fossicia* for the absence of earthy contamination. The first was by rubbing the material between one's hands to see if it made a noise, in which case it was good. The second was to wrap it in a white cloth and shake it up or beat it. If it did not stain the cloth then it was good and devoid of earth. The crunchy texture alluded to by Vitruvius occurs because the volcanic ash consists of vesicular volcanic glass that is broken with sharp edges.[21] Thus the ancient builders were aware of textural properties to distinguish ash from earth even if they did not have a consistent terminology.[22]

Volcanic ash is easiest to quarry when it is loose and unconsolidated, but consolidated deposits, called *tuff* (in Italian *tufo*), can also contain reactive material. In some English archaeological literature, this material is referred to as *tufa*, but that term indicates a calcareous rock and, to avoid confusion, is best not used in reference to volcanic materials. Some tuffs can be crushed and added to lime mortar to give it hydraulic properties,[23] though this process is more labor intensive than using loose volcanic ash. The fact that crushed tuff was occasionally used in ancient mortar is another indication that the Roman builders outside of Italy had a fairly sophisticated understanding of their materials.[24]

HOW DO POZZOLANS WORK?

The active ingredients in any pozzolan are soluble silica and alumina. Nonsoluble silica, such as quartz sand, has molecules that are more firmly bonded to each other so that it is not soluble and remains inert when mixed with lime and water. The silica and alumina in a pozzolan, in contrast, have been heated, either naturally (in a volcanic explosion) or artificially (in a kiln), and the molecular bond is weakened so that they can combine chemically with the lime and water. This chemical reaction creates a stronger bond within the mortar. As the silica unites with the lime, first a gel forms and then spikey crystals (strätlingite) appear. As more of these crystals are formed they interlock in matrix (think of Velcro), and the mortar becomes denser and stronger. Because the resulting product, calcium silicate hydrate (C-S-H), is insoluble, the mortar also becomes waterproof. The alumina is secondary to the silica and its role is less well understood, but recent investigations demonstrate that it likely had an effect on the noted longevity of Roman concrete.[25]

Pozzolans can have different degrees of *pozzolanic activity*, a term that refers both to the speed of the reaction and to the amount of C-S-H produced.[26] Two factors affecting the level of activity are the amount of soluble silica in the pozzolan and of the exposed surface area. The lapilli in volcanic ash tend to be very vesicular and provide a great amount of surface area without much processing. So, for example, *Puteolanus pulvis* is very good for underwater structures, in part because it has a large amount of soluble silica and comes in very fine particles. Both qualities aid in creating a fast-acting reaction, allowing the mortar to harden underwater faster than a mortar made with a less reactive pozzolan.

Some types of terracotta also make good pozzolans due to the silica and alumina in the clay that on firing become soluble and can combine with lime. However, both the firing temperature and the type of clay affect the ultimate reactivity. Most Roman pots, bricks, and tiles are made with illitic clay, which when fired at temperatures of 600–1,000°C becomes reactive with lime. The degree of reactivity increases as the temperature rises above 600°C until it reaches about 930°C and then begins to decrease.[27] Once it vitrifies at around 1,050°C it loses all reactivity; therefore the choice of terracotta is relevant in creating a good-quality hydraulic mortar. Bricks, amphoras, and coarse ware, which are fired around 800–900°C, would have been good choices, whereas terra sigillata fine ware, which is fired at temperatures at or above 1050°C, would not have been reactive.[28] The type of terracotta used in mortar mixes has rarely been studied, but J. T. Peña reports the use of utilitarian ware and cookware, including a piece from a Hayes 181 pan, in the crushed terracotta mortar at the amphitheater at El Djem in Tunisia, and J. Davis notes that coarse ware was used in the mortar lining of a cistern at Carthage.[29] Terracotta is a dense material and therefore must be ground finely to achieve a good pozzolanic reaction.[30] Crushed terracotta mortar hardens more slowly than mortar made with *Puteolanus pulvis* and is therefore less suitable for building underwater. However, it produces a denser mixture than mortar made with volcanic ash alone, so it is appropriate for waterproof linings, which was its most common application.

Kaolonitic clays were less commonly used in the Mediterranean than illitic clays, but they have the potential for a greater degree of reactivity with lime. Hence, they have been the subject of much modern research because they can provide an economical and environmentally friendly alternative to modern Portland cements. The Romans occasionally used kaolonitic clay to produce cookware because of its refractory properties and its resistance to thermal shock.[31] Deposits of kaolonitic clay from Gaul, Egypt, Lesbos, Cos, and Focea were used for pottery in Greco-Roman times.[32] These clays develop their greatest degree of reactivity at around 670°C (lower than illitic),[33] so kaolonitic pottery fired at higher temperatures would have been less desirable for making hydraulic mortar.

Ash from certain plants high in silica is another type of pozzolan. Many plants contain siliceous minerals called phytoliths, which when burned become soluble and can combine with lime to create hydraulic mortar. Phytoliths are particularly abundant in fast-growing annual plants such as cereals, like wheat and rye, and grasses and reeds. They are much less common in woody plants, which tend to have low levels of silica (Table 1).[34] The ashes of manure from herbivores also contain large amounts of soluble silica.[35] In fact, the use of wheat ash and herbivore manure ash as a replacement material for Portland cement is currently being explored.[36]

Hydraulic lime mortar can also be produced without adding additional pozzolans to the mix. Some types of limestone, such as marly limestone containing clay or limestone with diatoms (siliceous one-celled fossils), produce lime with enough soluble silica to create a hydraulic or semi-hydraulic mortar.[37] The naturally occurring silica in the stone is made soluble during the firing in the kiln, much like the silica in terracotta. Countries with suitable limestones for making hydraulic mortar include Britain, France, Greece, Tunisia, and Turkey.

TABLE 1. *Composition (%) of various organic ashes*

	Wheat Straw	Rye Straw	Lawn Grass	Olive Stones	Olive Press Cake	Oak Wood	Pine Wood	Poplar Wood
Silica SiO_2	55.32	49.27	39.64	30.82	21.20	15.30	10.00	5.90
Alumina Al_2O_3	1.88	–	16.60	8.84	2.90	0.13	0.43	0.84
Iron oxide Fe_2O_3	0.73	1.91	3.44	6.58	2.70	2.40	4.00	1.40
Calcium Oxide CaO	6.14	8.20	12.88	14.66	13.80	30.02	25.00	49.92
Magnesia MgO	1.06	3.10	5.65	4.24	8.40	12.01	6.32	18.40
Soda Na_2O	1.71	1.74	6.20	27.8	0.50	9.12	8.65	0.13
Phosphorus pentoxide P_2O_5	1.26	6.53	9.00	2.46	5.50	13.8	8.80	1.34
Sulfur trioxide SO_3	4.40	4.25	–	0.56	–	2.61	4.63	2.04
Potassium oxide K_2O	25.60	22.56	6.19	4.40	42.50	14.00	26.50	9.62

Wheat straw, olive stones, olive press cake, and poplar wood (Thompson 2008: 48, 54). Rye straw, lawn grass, oak wood, and pine wood (Rogers 1991: 26).

SURVEY OF REACTIVE ADDITIVES FOR MORTAR

Reactive additives, pozzolans, create hydraulic mortars that have greater compressive and tensile strength and acquire their strength quicker than simple lime mortars, thereby facilitating the construction process, an advantage noted by Vitruvius.[38] A visual inspection with a hand lens can often reveal the presence of crushed terracotta and larger pieces of volcanic ash in mortar, though sometimes the particles are so small that microscopic or chemical analysis is necessary. Both types of study indicate that some provincial builders were improving the quality of structural mortars by adding various types of pozzolans. Because this study focuses on the use of hydraulic mortar for buildings, I do not deal with the mortar employed for harbor installations, which appear to have often used the highly reactive *Puteolanus pulvis*.[39] Terrestrial structures, in contrast, can benefit from pozzolans with lower levels of reactivity.

Volcanic Ash. Examples of structural mortar with volcanic ash have been identified throughout the Mediterranean (WebCat. 2-A). In Turkey, which has numerous volcanic zones, mortars with volcanic ash have been found in various locales. In the Roman Baths at Sagalassos (mid-second century CE), the structural mortar contains an abundance of volcanic material, which corresponds petrographically to the local trachytic and trachyandesitic tuffs that were apparently crushed before mixing.[40] Volcanic materials (provenances undetermined) have also been found in the mortars of the foundation of the Temple of Apollo at Side (latter half of second century CE) and in the mortar joints in the brick walls of the Red Hall at Pergamum (second century CE).[41] A Hellenistic cistern at Pergamum contains crushed andesitic tuff in its waterproof lining, thus suggesting that use of the local volcanic materials in mortar may be a long-standing tradition there.[42] In Germany, volcanic ash has been found in the mortar of various monuments in Cologne: the aqueduct, a *horreum* (warehouse), and the city walls.[43] Though not confirmed, this material is likely from the nearby Eiffel volcanic zone where the reactive trass is still quarried for making concrete.[44] In the Crimea, where there are volcanic formations, volcanic ash (provenance undetermined) was found added to the mortar of a Roman bath in the military settlement of Charax and in an aqueduct at Chersonesus.[45] Finally, crushed volcanic material has been observed in the waterproof linings of Roman cisterns at Carthage and Uthina in Tunisia and at the volocanic island of Pantelleria.[46] The Carthage material was determined to be basaltic, whereas the Uthina material was trachytic/rhyolitic, thus suggesting different sources.[47] The material at Pantelleria was from local volcanic sources, which may have supplied Carthage as well.

The examples just cited indicate that, by the second century CE, builders in areas with easy access to local volcanic ash were occasionally adding it to waterproof plasters and to their structural mortar. The volcanic materials they used may not have always been as highly reactive as those found in central Italy, but they still created a stronger and more durable mortar that would have gained its strength quicker than a simple lime mortar. Moreover, the examples from Tunisia, which has no local sources of volcanic materials, suggest that there was a regional seaborne trade in volcanic ash separate from that of the renowned *Puteolanus pulvis*, which is known to have been exported for harbor construction.[48] But the evidence thus far suggests that the imported volcanic ash in Tunisia was used sparingly for waterproofing and special structural purposes.

Crushed Terracotta. As early as the first century BCE, Vitruvius recommended adding crushed terracotta to lime mortar to improve its structural qualities when *harena fossicia* was not available.[49] Crushed terracotta mortar, also referred to as *cocciopesto* or *opus signinum*,[50] is the most common waterproof lining for liquid containment structures throughout the empire (WebCat. 2-B), but its use in structural mortar seems to have become more common over time (Fig. 9C). In France, it was used in the walls of the Temple of Janus at Autun (first century CE?) and of various bath buildings: at Escolives, Charente, Vienne, and Arles (early second century CE).[51] In Turkey, it was used as the mortar of *opus testaceum* walls in the amphitheater at Cyzicus,[52] and in Bulgaria it is found in the mortar at various sites including the amphitheaters at Marcianopolis and Hysaria.[53] In Jordan, a sample of structural mortar of the Ghana aqueduct at Humayma (late first century BCE/early first century CE) contained structural mortar with crushed terracotta, though this seems to have been exceptional, with most examples of terracotta mortar from the site coming from plaster linings.[54] Crushed terracotta mortar was particularly common in Britain and was used for large and structurally challenging vaults. It can often be found still attached to hollow terracotta voussoirs (see Chapter 6). One of the most impressive examples occurs in the vault from the Great Bath of the Sanctuary of Sulis Minerva at Bath (late second century CE?). By the Byzantine period, crushed terracotta mortar was very common, as can be seen in numerous early Byzantine structures in Ravenna and Istanbul, most notably the Hagia Sophia.[55]

Organic Ash. Mortar containing pozzolans of organic ash from burnt plant remains and manure may be more common than has been realized. When mortar containing burnt material is reported, it is often described as containing pieces of charcoal, which is not a pozzolan. Charcoal is formed by the imperfect combustion of organic material, which results in a substance consisting mainly of carbon, whereas ash is the completely burnt remains of organic material consisting of mineral remains, among which can be silica. In mortar studies, therefore, the distinction between charcoal and ash is important. An example of the type of ambiguity that can arise occurs in the report of a mortar from the lining of a pool in a Roman bath at Calahorra (ancient Calagurris Nassica), Spain (first to third century CE); there it is described as containing abundant charcoal "deliberately added to the mortar as a pozzolan," thus implying that charcoal is reactive with the lime.[56]

A common explanation for the existence of charcoal in lime mortar is that it represents contamination from the fuel used in the limekiln. This phenomenon may well explain how ash mortar was invented, but the practice of adding organic ash and charcoal eventually became intentional. Charcoal itself is unlikely to have been used as fuel for burning lime,[57] but it may have been a product of the process in the form of remnants of carbonized fuel along with the resulting ashes. A type of fuel often used in areas without access to wood was dried manure, which can produce a highly reactive ash.[58] Theophrastus, writing in the late fourth century BCE, notes that in Phoenicia and Syria cow manure was used as fuel to accelerate the calcination of stones.[59] This practice may have led to the discovery that the ashes from the limekiln (and elsewhere) could create a hydraulic mortar. Mortar containing burnt organic material (ash/charcoal) is particularly common in areas of the Levant (Fig. 9D), and in the West examples are found mainly in areas of Punic influence: North Africa, Sardinia, the southern coast of Spain, and Pantelleria. The distribution pattern suggests that the practice in the West could have Phoenician origins, as implied by Theophrastus's comment. Further studies are needed to determine the origins, nature, and physical characteristics of ash mortar.[60]

A majority of the examples of ash mortar come from the linings of baths or liquid containment structures, but a few come from structural mortars as well (WebCat. 2-C). The mortar samples from the walls of the House of the Charioteer at Carthage have been analyzed for content, but not for structural properties, and provide some insight into the ash mortar used in structural contexts. The most common remains in the mortar were olive pits, but other types of plants were also found, including wheat, barley, rye, canary grass, and figs, all of which contain large amounts of soluble silica.[61] Recent analysis of the burnt remains in pottery kilns at Leptiminus revealed olive pits, suggesting that olive pressings were commonly used as fuel.[62] Given the role of olive production in North Africa this is not surprising. Studies of the chemical composition of ashes from burnt olive pits and pressings reveal that they can contain significant amounts of silica: 31 percent for the pits and 21 percent for the pressings (Table 1). The other grasses and grains found in the Carthage mortar would contain even larger amounts of silica, with wheat straw ash reaching as high as 68 percent. Even the burnt remains of figs, which are one of the few fruits that contain high levels of phytoliths, could have reacted with lime.[63] The second-century walls contain burnt olive pits and plant tissue, whereas the walls dating from the fourth to the sixth centuries CE contain remains of burnt grains.

Other examples of structural uses of ash mortar occur at Leptiminus and Alexandria. At Leptiminus, a systematic analysis undertaken on mortars relating to hydraulic structures, including the vaults of two cisterns (undated), revealed that various pozzolans were used together in both waterproof linings and structural vault mortar: crushed terracotta, charcoal (presumably with ash), and siliceous limestone.[64] In Alexandria, the substructure vaults of the late fourth-century CE Baths of Kom El-Dikka were built with mortar containing the ash of straw and reeds,[65] both of which contain high levels of soluble silica. Thus, builders in North Africa were adding organic ash to their structural mortars at least occasionally by the second century, but in general the practice appears to have become more common later. The ashes and charcoal bits may well have come from the limekiln, but if they were added intentionally they could just as easily have been collected from pottery kilns and even domestic contexts, as implied by the Carthage mortar study. Ultimately there are not enough examples to make a claim for ash mortar having a significant effect on the development of vaulting; however, the fact that it seems to be a characteristic mortar type found in Punic areas makes it a type of marker that can provide some insight into possible cultural links when it is found (see Chapter 5 conclusions).

Naturally Hydraulic Lime. Finally, there is the question of the use of naturally hydraulic lime, which is acquired by burning limestone containing silica. J.-P. Adam suggested that Roman builders always used nonhydraulic lime, but this idea was based on a single study of mortars from France,[66] whereas other evidence suggests that the practice may have varied by region (WebCat. 2-D). The analysis of the mortar from a cistern at Leptiminus found siliceous limestone to have been used.[67] In Britain at the Park Street Villa near St. Albans, the excavator was fortunate to find lime in a slaking pit (mid-second century CE) before it had been made into mortar: Analysis revealed that it was semi-hydraulic "similar in composition to the present-day local greystone cretaceous limes of the Luton-Dunstable area."[68] In the Levant, recent analysis of first-century CE mortars (not structural) from Petra (Great Temple, Palace, and Pool Complex) and Damascus (Temple of Jupiter) shows the presence of the clay minerals, illite and kaolinite, which suggests the use of local marly limestone to create hydraulic or semi-hydraulic mortars there.[69]

Mortar analysis has become much more common in the past several decades due to the use of more advanced analytical methods, an increased interest in preservation techniques, and the desire of developing countries to find alternative uses for local natural resources as potential substitutes for Portland cement. The scientific literature on the analysis of ancient mortar has expanded dramatically, and the advent of electronic publishing has made the results of such research more widely available across disciplines than in the past. The examples discussed earlier illustrate the potential for discovering the degree to which the Romans were employing these other sources of pozzolans. However, because many of these examples have not come from vaults, questions remain as to the degree to which builders outside of central Italy made significant attempts to create hydraulic mortar for large vaulted structures employing *opus caementicium*. Is there a difference between the mortar used in walls and vaults of a single structure? Are patterns of use in mortar types associated with particular types of vault construction, such as voussoirs of brick or stone? Are there regional patterns of mortar types for vaults? Answering these questions requires a systematic study using consistent analysis types that extends across regions and focuses on the largest vaulted structures, which are the ones most likely to have employed special mortar – a model is the ROMACONS project for the study of mortars used in harbor construction.[70]

CAEMENTA: SOURCES OF STONES AND STRUCTURAL STRATEGIES

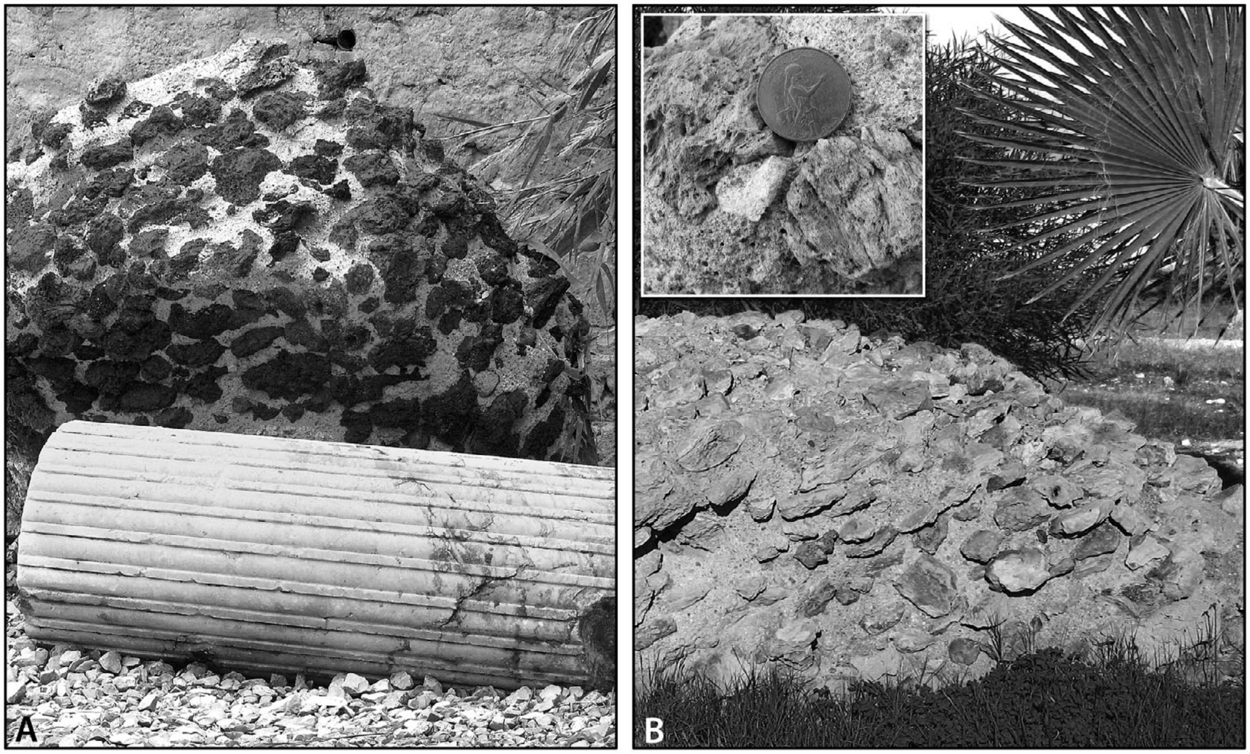
One of the great advantages of *opus caementicium* for vaulted structures was that it enabled the use of lightweight stones in the uppermost part of the vault and heavier stones in the haunches, thereby reducing its lateral thrusts pushing the walls outward. In Rome, the selective use of different types of rocks for *caementa* occurs from the mid-first century BCE,[71] but the systematic use of imported lightweight rocks for vaulting only began in the early second century CE under Trajan (WebCat. 2-E).[72] The most sophisticated application of this principle occurs in the vault of the Pantheon where lightweight volcanic scoria (750–850 kg/m^3) imported from Vesuvius on the Bay of Naples was used along with local, lightweight tuff, Tufo Giallo della Via Tiberina (1350–1450 kg/m^3), at the crown of the dome and heavier Tufo Lionato (1600 kg/m^3) and brick (1750 kg/m^3) at the haunch. The same scoria was used in the vaults of the great imperial thermae of Trajan and Caracalla.[73] During the second century, the technique of using lightweight stones for vaults spread outside of Italy throughout the empire (Fig. 9B).

The use of volcanic scoria in vaulting was for the most part a regional phenomenon with distribution within a 25 km radius of the source. In eastern Sicily, the volcanoes of Etna and Hyblea were the likely source of the scoria used in the theater at Taormina (second quarter of second century CE), the odeum at Catania, and the "Gymnasium" at Syracuse.[74] In the Jabal ad Druze volcanic zone of southern Syria, the baths at Philippopolis (max. 11 m span) and the South Baths at Bosra (max. span 10.8 m cross; 15.0 dome) both employ volcanic scoria in their vaults and are located within 20 km of scoria cones.[75] In Smooth Cilicia, the Ceyhan-Osmaniye scoria cones of Delihalil Tepe, Uçtepeler, and Gertepe produced scoria (1235 kg/m^3) used in bath buildings at Castabala Hieropolis and in the fallen vaults of the North Bath at Anazarbus (WebFig. 3).

Seaborne trade in lightweight volcanic stones is also attested. We know that builders in Rome imported scoria from the Bay of Naples for use in vaults,[76] but elsewhere evidence for trade is rare. In Smooth Cilicia, scoria appears in the upper parts of the vault of the baths at Tarsus (WebFig. 3), which is about 100 km to the west of the scoria cones and was likely supplied by sea.[77] In Africa Proconsularis, examples of lightweight volcanic stones have been found in vaults at Carthage on the north coast and at Leptiminus on the east coast. Each employs a different type of lightweight volcanic stone, which is telling because the area is not volcanic, and thus these examples provide insight into trading patterns around the Sicily Channel, a connector between the eastern and western halves of the Mediterranean.

At Carthage, a dark brown to reddish scoria (1220 kg/m^3) is found in a number of vaults including the Antonine Baths, which are among the handful of buildings with vaults with a span larger than 18 m (WebCat. 1). The scoria in these vaults was noted as early as the eleventh century by the geographer Al-Bakri,[78] but very little of the upper level vaults survives today. One piece remains at the north end of the complex (Fig. 10A, WebFig. 4). In the past, the provenance of this material has been assumed to be either Sicily or Sardinia, with Sicily preferred given that the scoria there was already being used at Taormina and Syracuse.[79] However, recent geochemical analysis using trace elements has determined that it originated in Sardinia, which was one of the main suppliers to Carthage of millstones made from the local volcanic lava.[80] The scoria likely arrived at Carthage as a secondary product along with the millstones. Given the quantity of scoria that would be needed for the vaults of such a large structure, the material was probably specially ordered, but the fact that there was an established shipping route for the millstones would have made such orders economically feasible. Large blocks of similar looking scoria were also imported to be used as the *pilae* in hypocausts,[81] presumably because of their fireproof qualities.

That Sardinia was the source as opposed to Sicily for the scoria at the Antonine Baths is also informative from a navigational perspective (Fig. 11). The ports along the eastern coast of Sicily lead into the Strait of Messina, which was often treacherous due to winds and difficult currents,[82] whereas the Sardinian



10. Lightweight volcanic stones in Tunisia. A: Antonine Baths, Carthage (146–162 CE). Chunk of fallen vaulting with *caementa* of dark volcanic scoria imported from Sardinia. B: East Baths at Leptiminus (late second century CE). Chunk of fallen vaulting with admixture of light colored pumice imported from Pantelleria. (Color images: WebFigs. 4–5).

ports of both ancient Tharros and Carralis provided a direct and easy voyage to Carthage. In particular, ships embarking from ports in Spain or Gaul to Carthage would have had a favorable wind for traveling toward the west coast of Sardinia en route to Carthage. The study of deepwater shipwrecks along the Skerki Bank north of Carthage has shown that many of the ships were carrying a mixed cargo, suggesting that even ships making deepwater crossings were picking up goods in route.[83]

At Leptiminus, the provenance of the light gray/brown pumice (600 kg/m^3) in the fallen vaults of the *frigidarium* (c. 10 m span) of the East Baths tells a different story (Fig. 10B, WebFig. 5). Microscopic analysis revealed that it contained a rare mineral, aenigmatite or cossyrite, which takes its name from the ancient name of the volcanic island, Cossyra, modern-day Pantelleria. The result was somewhat surprising because the anticipated source was the Aeolian Islands, which were mentioned by Pliny as a source of light-colored pumice.[84] Pantelleria was a major navigational hub in the Sicily Channel and had a particularly important role in the transhipment of goods to and from North Africa (Fig. 11).[85] As with Sardinia, Pantelleria was a source of millstones made of basaltic lava that have been found at Carthage, Utica, Thuburbo Maius, Celibia, and El Maklouba in Tunisia and more recently at Cyrene in Libya.[86] The island had little to offer in terms of agricultural surplus and therefore took advantage of its role as a port of call to develop an export trade in millstones and in a locally fabricated cookware,

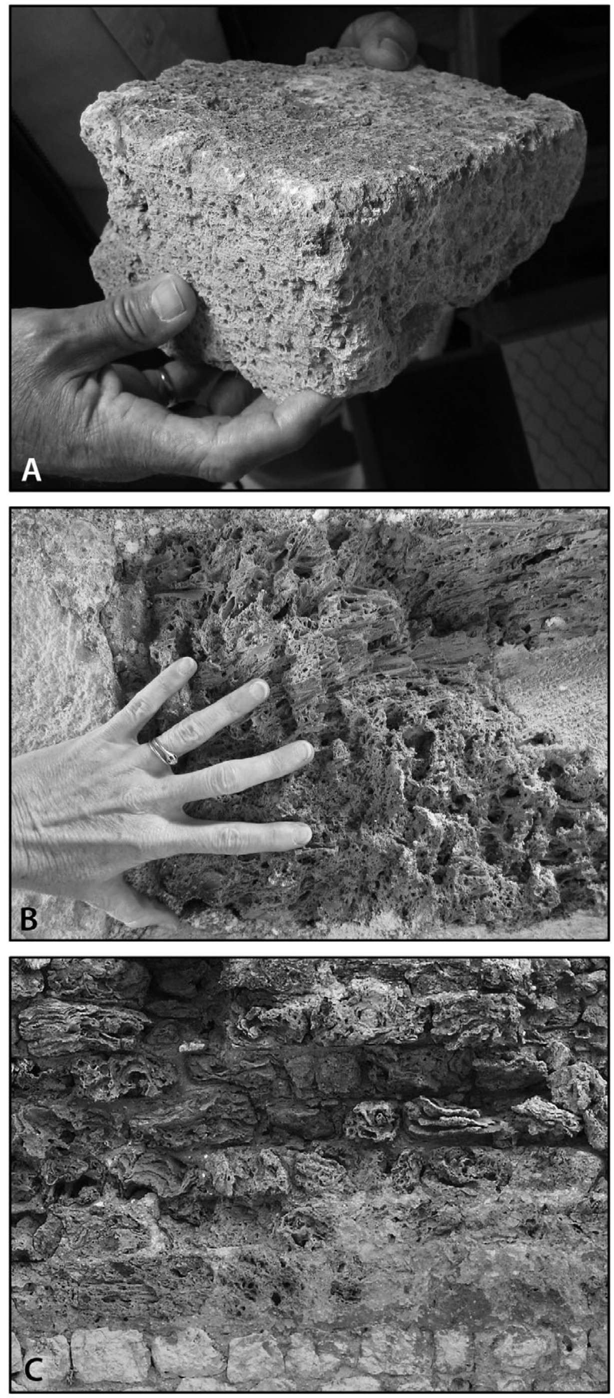
11. Map showing locations of volcanic systems (hatched areas) and navigational routes around Sicily (based on Arnaud 2005: figs. 154–55).

Pantellerian Ware.[87] Thus, as with the Sardinian scoria in the vaults at Carthage, the pumice in the vaults of the East Baths at Leptiminus can be explained as part of a regional trade network, in this case emanating from the navigational hub of Pantelleria. The recent finding of local volcanic ash in the hydraulic mortar of Pantellerian cisterns suggests that its exports may have included reactive volcanic ash as well.[88] In both cases, the volcanic building materials were likely secondary export items, with millstones and pottery taking precedence.

In nonvolcanic zones, calcareous tufa was often used as *caementa* or as voussoirs in vaults. The weight of tufa can vary greatly according to its formation and density, but an average porosity yields stone weighting 1,350 kg/m^3,[89] which is the same weight as the volcanic yellow tuff used in the Pantheon dome. The porosity of tufa also gives it a low thermal conductivity (k = 0.55 W/mK as opposed to 0.70 W/mK for brick and 1.30 W/mK for limestone) and better insulating properties, which would have been a particularly advantageous property in baths. Tufa is available in many parts of Britain and was commonly used in vaults throughout the province. At the bath of a villa at Newport on the Isle of Wight, the apses of the rooms (2.1–2.8 m span) were built of tufa that had evidently been imported from mainland Britain, given that it is not available locally (Fig. 12A).[90] At such a tiny bath, one wonders if the choice to import tufa from the mainland was based more on its thermal properties than any structural advantages.

The use of calcareous tufa for vaulting was wide ranging in the empire and was dictated by its availability. At Diocletian's Palace at Split a local tufa, known as *sedra*, was employed extensively in the vaults of both the substructures and superstructures (Fig. 12B). In the substructures it was typically laid radially in a crushed terracotta mortar, often with courses of radially set brick running at intervals (Fig. 13A, WebFig. 6A).[91] In Rough Cilicia at Elaeussa Sebaste, the builders of the Agora Baths employed a local calcareous tufa in the vaults (6.1–9.2 m span) while using a denser limestone for the walls (Fig. 12C). The same type of vesicular calcareous stone was used in the vaults of numerous baths in this region (WebCat. 2-E). In southeastern Spain, a type of mid to lightweight calcarenite, locally known as *piedra fosca* was used for the stones making up the vaults of the baths at Labitolosa.[92]

A characteristic feature of *opus caementicium* vaults in imperial Rome is that the *caementa* were laid horizontally rather than radially like voussoirs. The change in the orientation of the *caementa* is attributed to the high-quality pozzolanic mortar that gained its strength much more quickly than simple lime mortar, so that the centering could be removed without having to rely on the voussoirs to resist the stresses in the vault. The vaults of *opus caementicium* in the provinces often have the *caementa* set radially, which has been presumed to be necessitated by the absence of pozzolanic mortar, but there is actually great variation in the way the *caementa* are set. Sometimes they are long and thin so that they form an arched shell of roughly shaped voussoirs, as at the theater at Aphrodisias (late first century BCE), the substructures of the Temple of Asclepius at Pergamum (second quarter of



12. Examples of lightweight calcareous tufa in vaults. A: Voussoir from the baths at the villa at Newport, Isle of Wight (c. 280 CE). B: Piece of *sedra* in a vault at Diocletian's Palace at Split, Croatia (early fourth century CE). C: Impost of vault at the Agora Baths at Elaeussa Sebaste showing the transition from limestone *opus vittatum* in the walls to the calcareous tufa in the vault.

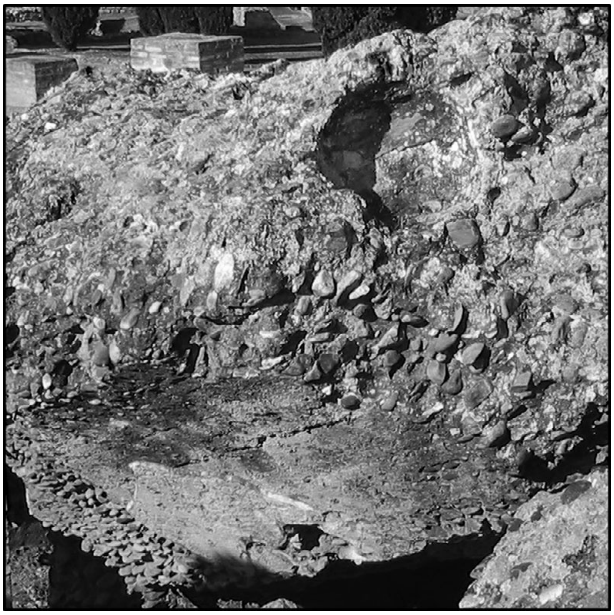
13. Examples of radially laid *caementa* combined with courses of radially laid brick. A: Substructures of the Palace of Diocletian at Split, Croatia (early fourth century CE). B: *Praefurnium* for *caldarium* of the Imperial Thermae at Trier, Germany (early fourth century CE). Note vertical tubes in vault for ventilation. The iron tie bars are modern. (Color image: WebFig. 6).

second century CE), and the amphitheater at Salona (Figs. 14A–B). A variation on the idea occurs in the barrel-vaulted *praefurnium* (furnace) of the *caldarium* of the Imperial Thermae at Trier (Fig. 13B, WebFig. 6B), where radially laid stone slabs alternated with courses of brick similar to the example at Split (Fig. 13A).[93] Presumably these radial courses of brick were meant to divide the sections of *opus caementicium* into wedge-shaped blocks to act as voussoirs and to ensure an even distribution of forces through the vault.

Other times smaller *caementa* were set in a radial pattern without actually forming a distinct arched layer along the intrados, as at the Baths of Memmia at Bulla Regia (Fig. 15A, WebFig. 24) and the substructures of the baths at Antiochia in Pisidia (Fig. 15B). In such cases, the stones were so small that they are unlikely to have had much structural benefit. Examples also exist where small unformed *caementa* were set horizontally or randomly, as in the fallen vault at the Casa de la Esedra in Italica, which employed smooth river stones (Fig. 16), and the vaults of the amphitheater at El Djem. In Greece, the baths at Thouria (max span 5.5 barrel, 6.0 cross) have the *caementa* set horizontally (mortar type unknown), as do the Great Baths on the Lechaion Road at Corinth (max span 10.7 m barrel, 11.6 m cross) where the

14. Examples of long narrow *caementa* laid radially. A: Amphitheater at Salona, Croatia. B: Substructure of Temple of Asclepius at Pergamum, Turkey.

15. Examples of small irregular *caementa* laid radially. A: Entry vestibule in Baths of Julia Memmia at Bulla Regia, Tunisia (c. 230 CE) (see plan in Fig. 79). B: Bath at Antiochia in Pisidia, Turkey.



16. Casa de la Esedra at Italica, Spain (second century CE). Note the formwork imprints along the intrados and the use of smooth river stones set randomly in the mortar. The circular indentation at the top right is the impression of a Dressel 20 amphora, which was one of a number that were embedded in the vault (Lancaster 2005a: 70–71).

mortar has been determined to have volcanic additives.[94] Both have horizontal courses of brick set at intervals within the vault, which represents a different conception from the radial ones mentioned earlier. At the volcanic island of Cos the *caementa* were set randomly in the West Baths (second half of the second century CE). The island has abundant deposits of volcanic ash that were used into the twentieth century for making hydraulic mortar, though the mortar in the ancient structures has not been analyzed.[95]

The relationship of the type of mortar to the type of *caementa* and the way they are put in place would be useful information for understanding the evolution of *opus caementicium* vaults outside Italy, particularly for those employing lightweight *caementa*. The baths in Cilicia at Tarsus and Anazarbus have the volcanic scoria set horizontally, but the crowns do not survive to indicate how they were constructed (WebFig. 3). Both examples were divided into horizontal layers by courses of brick much like those at Thouria and Corinth. Given the location of these structures, as well as the ones at Philippopolis and at Bosra in Syria, all in volcanic zones, one would expect the mortar to contain volcanic ash, but the mortar in these structures has not been examined to determine their ingredients or strength.[96] Clearly there was great variation in the approach to constructing vaults of *opus caementicium* throughout the empire. Whether the variation in the size, type, and orientation of the *caementa* was directly related to the strength of the mortar used is a question that requires further systematic analysis.

CONCLUSIONS

A survey of the mortar and the types of lightweight *caementa* available to Roman builders outside of Italy has shown that the builders in the provinces had a greater choice of materials (the technology shelf) from which to choose than has generally been acknowledged. The Romans are usually credited with the invention of concrete, which in turn was dependent on the adoption of the high-quality mortar produced from the volcanic ash in central Italy. But the builders of central Italy were not working in a vacuum. Analyses of pre-Roman hydraulic mortars from other parts of the Mediterranean reveal a long history of development that goes back to the second millennium BCE. Volcanic ash has been identified in the mortar of a Late Minoan cistern at Chania, Crete, and crushed terracotta has been found in mortar in the courtyard of the Mycenaean palace at Tiryns.[97] The regular use of crushed terracotta mortar for waterproofing and for the bedding of tesserae floors began around the end of the fourth or beginning of the third century BCE; examples have been found in Greece, Sicily, southern Italy, and Tunisia. Thus the use of hydraulic mortar in nonstructural contexts seems to be a phenomenon of the Greco-Punic world before being adopted in central Italy.[98] However, a sixth-century BCE cistern from Cameiros on Rhodes has walls built with mortar containing volcanic ash, which suggests that there may have also been some Greek experimentation with structural mortars.[99]

The major contribution of the builders in central Italy to architectural development was to recognize that the technology for making a hydraulic mortar also made it much stronger. Vitruvius clearly understood this when he recommended that crushed terracotta be added to structural mortar if *harena fossicia* was not available.[100] The development of *opus caementicium* in Rome has usually been dated to the late third century BCE,[101] but with the recent questioning of the *opus incertum* structure in Testaccio as Livy's "*porticus Aemilia*,"[102] the chronological fix point of 174 BCE for concrete vaulting in Rome no longer holds.[103] In fact, a recent study argues for the development of *opus caementicium* walls as not earlier than the mid-second century BCE,[104] so the Roman use of concrete in central Italy may be somewhat later than previously thought. Nevertheless, once builders began to use this new material, they changed the way in which structures were conceived both spatially and structurally. Thus the *invention* of hydraulic mortar goes back to the Bronze Age, but the *innovation* of applying this technology to standing structures, particularly vaulted ones, was accomplished by builders in central Italy by the second half of the second century BCE.[105] The use of mortar-based construction for walls and vaults then spreads outside of Italy by the beginning of the first century CE.

The other ingredient of *opus caementicium* that made possible the largest and most daring vaults in Rome was lightweight *caementa*. Outside of Italy, the use of lightweight stones varied by region. Volcanic scoria and pumice were used in volcanic zones, and calcareous tufa was commonly used in nonvolcanic areas when available. There was a general tendency toward using lighter *caementa* for vaulting when possible, especially in bath buildings, which usually required the largest vaults. Moreover, lightweight *caementa* often had insulating properties that made them particularly advantageous for baths.

The findings of imported volcanic materials in Tunisia indicate that there was also seaborne trade in nondecorative building stone, including both lightweight *caementa* and volcanic ash. That there was likely a Mediterranean-wide trade in the highly prized *Puteolanus pulvis* from the Bay of Naples has been recognized,[106] but the regional trade in these less renowned volcanic building materials is more surprising. The scoria at Carthage came from Sardinia and the pumice at Leptiminus from Pantelleria. Both islands were trading hubs in the western Mediterranean that exported millstones to North Africa, so the builders appear to have been using existing trade connections to acquire their material. For the Antonine Baths at Carthage, which are among the largest structures outside Rome, the fact that the Vesuvian scoria used in the Pantheon dome was *not* used is telling. It is the best of the available types of scoria because it is very strong (unlike pumice), but it is lighter (750–850 kg/m^3) than the scoria from other volcanic systems (1,220–1,235 kg/m^3). After the addition of Trajan's harbor at Portus, the grain shipments destined for Rome from Carthage could bypass the harbor at Puteoli on the Bay of Naples, which in turn may have made the volcanic materials from the nearer volcanic islands more appealing, because they were already part of the regional trade network. Rome, in contrast, continued to be closely connected to the major port at Puteoli, so acquiring the Vesuvian scoria for projects in the capital would not have been problematic.

Ancient builders in most parts of the empire had access to materials for making some form of *opus caementicium* if they decided to use it for their vaults. To what degree they added pozzolans to their mortar mix for the vaulting mortar can only be determined by a more systematic program of analysis. Further studies should take into account the constituents of the mortar, the type of *caementa*, and the way in which the *caementa* were laid in the mortar. In mortar analyses, determining the ingredients used in the mortar can give some idea about trade if provenance can be determined. However, identifying the presence of volcanic materials in a mortar does not ensure that it is hydraulic or even stronger than a simple lime mortar. The next step is to determine whether or not a pozzolanic reaction has occurred by checking for the development of calcium silicate hydrates (C-H-S). A comparison of those results with the size, type, and orientation of the *caementa* could then provide some clarity on how the builders in different regions were thinking about their concrete vaulted structures and the degree to which using simple lime mortars actually inhibited the size of vaulted structures.

The use of hydraulic mortar and lightweight volcanic stones certainly acted as a catalyst in central Italy for developing new forms and larger spaces, but the availability of riches in central Italy was not the only source of inspired creativity in the empire. "Necessity is the mother of invention," so goes the old adage. In the following chapters I explore techniques that builders outside Italy employed using man-made elements of terracotta as an alternative way of building vaults.

3

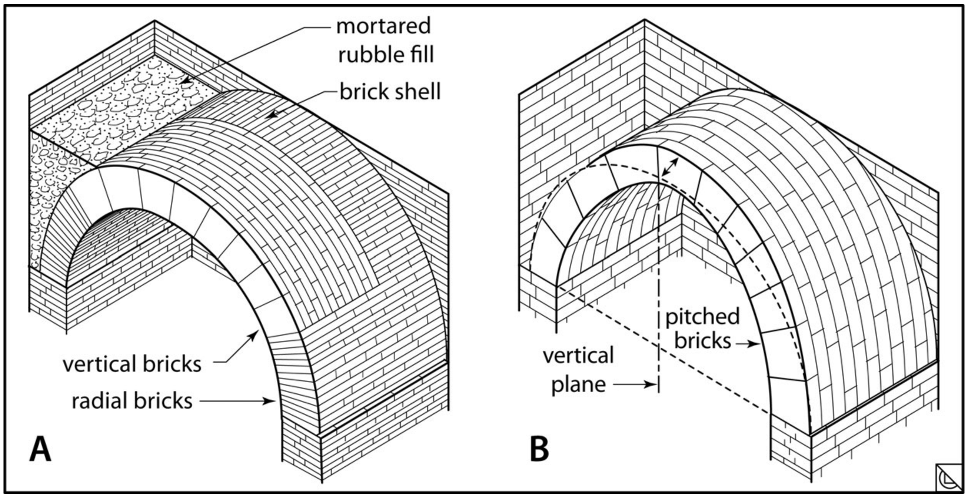
BARREL VAULTS OF BRICK

Once vaulted construction was adopted outside of Italy, bricks were often substituted for the radially laid *caementa* of unhewn stone. A brick vault usually consisted of a brick shell forming the intrados with a fill of mortared rubble above it (Fig. 17A).[1] The different materials resulted in a distinct joint between shell and fill. Often the bricks have fallen away or been removed for reuse, leaving only mortared rubble. Yet careful examination can sometimes reveal traces of the bricks or their imprints on the mortar of the fill. In fact, brick vaults, especially in bath buildings of Greece and Asia Minor, were more common than has been represented in earlier literature (WebCat. 3-A).

When bricks were used instead of cut stone, they were clearly meant to act as voussoirs even when they did not take a wedge-shaped form. Both stone and brick vaults were considered to be stronger. than mortared rubble construction (*opus caementicium*). In Rome, the builders often reinforced their concrete vaults with radially set voussoirs of cut stone or brick at points of stress. The earliest example of such reinforcement (in stone) occurs in the Late Republican Sanctuary of Hercules Victor outside of Rome at Tivoli (mid-first century BCE).[2] Once brick became part of the constructional vocabulary it replaced cut stone as the primary material used for reinforcing vaults, as in an early example at the Colosseum (80 CE).[3] Solid brick vaults were also used in some unusual situations to provide greater stability, such as recently demonstrated for the Mausoleum of Hadrian,[4] but brick was rarely employed as the primary vaulting material in Rome.

The use of bricks in place of stone voussoirs had a long history before it ever appeared in Rome. In southern Italy, three third-century BCE tombs outside Reggio Calabria were built with vaults of radially laid bricks specially formed into wedge shapes. Some of the wall bricks were stamped with the Greek name, Memnon in the genitive (ΜΕΜΝΟΝΟΣ), a stamp that also appears on roof tiles in the region. Memnon seems to have supplied a variety of different terracotta building materials, and he apparently added voussoirs to his repertoire.[5] Brick vaulted tombs are also known at Norcia (ancient Nursia) from the second century BCE (largest 3.7 m span).[6] Another brick vaulted tomb (first century BCE) was found at Sarsina in northern Italy (Emilia Romagna),[7] and brick arched windows were used in the mid-first century BCE fortification walls at Verona.[8] Clearly the practice

Catalogs (WebCat.) and color figures (WebFig.) can be downloaded at www.cambridge.org/vaulting



17. Drawings showing methods of laying brick for vaulting. A: Fired-brick vault with radial bricks at haunches and vertical bricks at crown. B: Mud brick vault with bricks laid at an angle, or pitched, against the back wall.

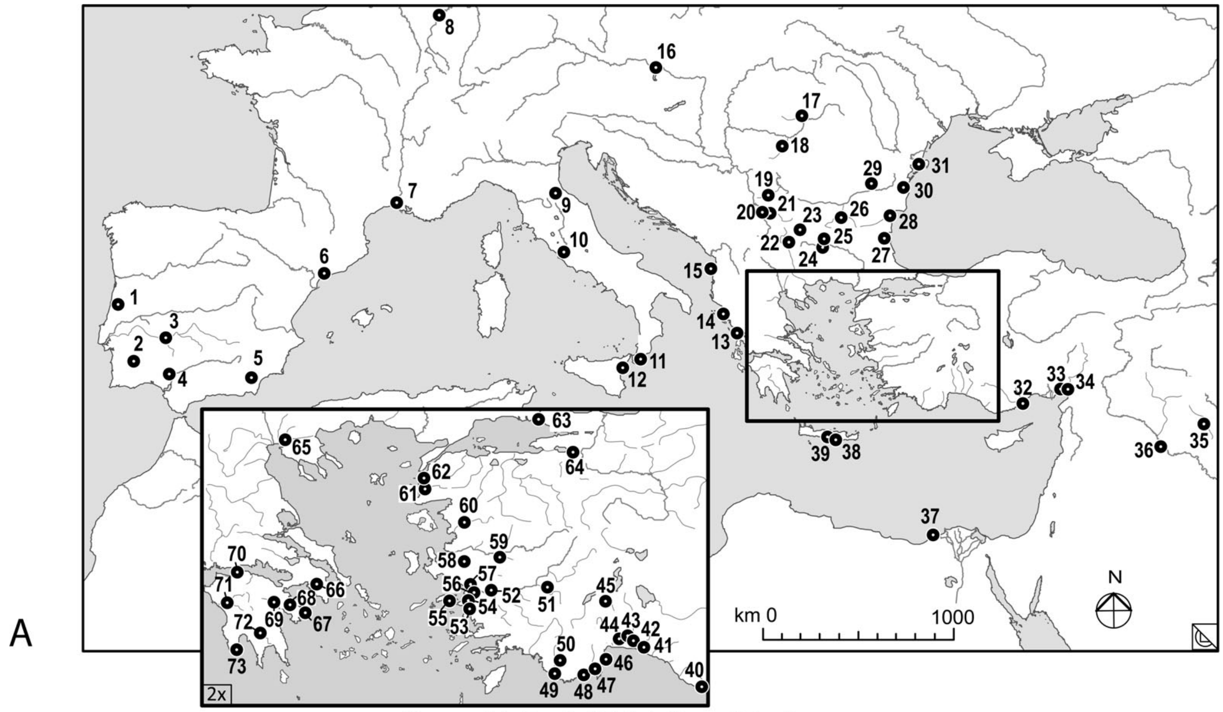
was not a new one when builders at the Colosseum decided to substitute bricks for cut stone voussoirs as a means of reinforcing the vaults there. Bricks were much easier to form and to handle, and after the fire of Nero in 64 CE, brick production increased so there were many more available. As in Rome, the choice to use bricks for vaulting in the provinces must have been affected by the production infrastructure in a given area.

In the following discussion, I limit the geographical range to the eastern Mediterranean, primarily Greece and Asia Minor, because that is where most of the examples occur (Fig. 18). I also focus exclusively on barrel vaults in this chapter because the ways in which the bricks were placed in more complex forms, such as cross vaults, sail vaults, domes, and semidomes, raise different questions, which I examine in Chapter 4. Brick arches and vaults were commonly used in the hypocausts of baths and the idea was presumably borrowed directly from kiln technology where it is also commonly found in firing chambers.[9] However, these small structures represent a different phenomenon from the much larger vaults of the superstructure, so I have not included them in this study.

This chapter addresses the following questions: When and where in the empire did the use of brick for barrel vaults first occur? What are the factors that influenced its adoption? Why were the bricks sometimes laid vertically rather than radially? What were the sources of inspiration for this new method of laying the brick?

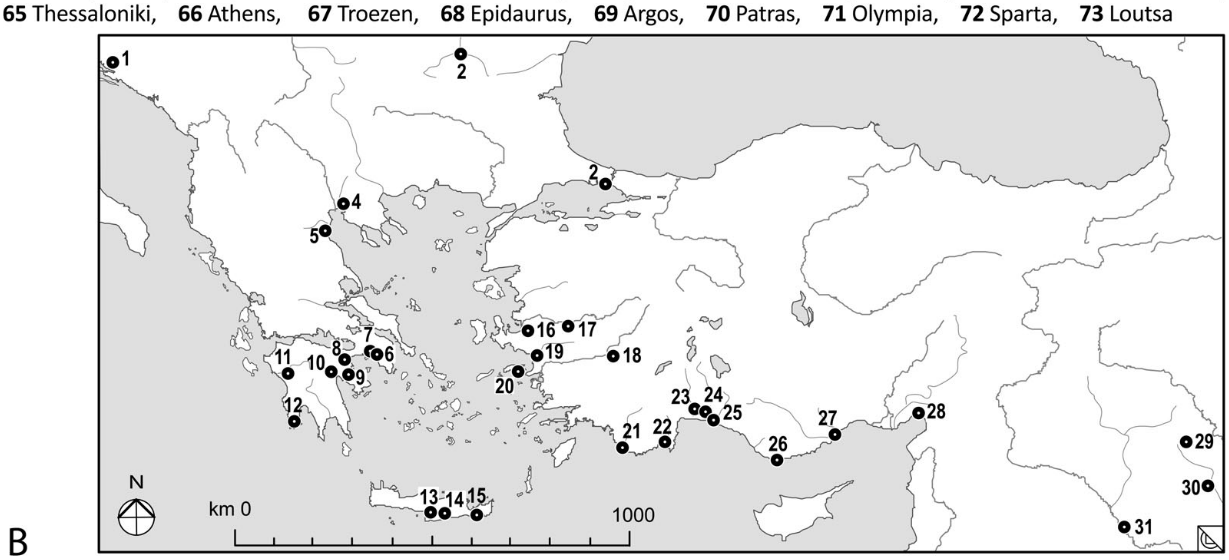
METHODS OF CONSTRUCTION: TERMINOLOGY

The most common method of laying the bricks in Roman vaulting was to place them radially, like the voussoirs of an arch, but another method, often called pitched brick vaulting (Fig. 17B), was used in some areas. This was an adaptation of a much older Near Eastern and Egyptian technique that was used in mud brick architecture from at least the third millennium BCE.[10] The term *pitched brick* was coined because in these early mud brick examples the first ring of bricks was placed at a slight angle against the back wall of a structure (i.e., pitched);



Sites with Radial Brick Barrel Vaults

1 Coimbra, **2** São Cucufate, **3** Mérida, **4** Italica, **5** La Alberca, **6** Centcelles, **7** Arles, **8** Trier, **9** Sarcina, **10** Rome, **11** Reggio Calabria, **12** Taormina, **13** Nicopolis, **14** Butrint, **15** Durres, **16** Carnuntum, **17** Turda, **18** Sarmizegatusa, **19** Gamzigrad, **20** Mediana, **21** Naissus, **22** Kadim Most, **23** Sofia, **24** Plovdiv, **25** Hysaria, **26** Nicopolis ad Istrum, **27** Anchialos, **28** Varna, **29** Durostorum, **30** Constanta, **31** Halmyris, **32** Elaeussa-Sebaste, **33** Küçük Bernaz, **34** Erzin, **35** Hatra, **36** Dura-Europus, **37** Alexandria, **38** Castelliana, **39** Gortyn, **40** Anemurium, **41** Side, **42** Aspendus, **43** Silyon, **44** Perge, **45** Sagalassus, **46** Phaselis, **47** Rhodiapolis, **48** Myra, **49** Patara, **50** Tlos, **51** Hierapolis, **52** Tralles, **53** Miletus, **54** Priene, **55** Samos, **56** Magnesia on Meander, **57** Ephesus, **58** Izmir, **59** Sardis, **60** Pergamum, **61** Alexandria Troas, **62** Troy, **63** Istanbul, **64** Nicea, **65** Thessaloniki, **66** Athens, **67** Troezen, **68** Epidaurus, **69** Argos, **70** Patras, **71** Olympia, **72** Sparta, **73** Loutsa



Sites with Vertical Brick Barrel Vaults

1 Mogorjelo, **2** Nicopolis ad Istrum, **3** Istanbul, **4** Thessaloniki, **5** Dion, **6** Athens, **7** Eleusis, **8** Isthmia, **9** Epidaurus, **10** Argos, **11** Olympia, **12** Loutsa, **13** Gortyn, **14** Castelliana, **15** Macrygialos, **16** Izmir, **17** Sardis, **18** Aphrodisias, **19** Ephesus, **20** Samos, **21** Patara, **22** Rhodiapolis, **23** Silyon, **24** Aspendus, **25** Side, **26** Anemurium, **27** Elaeussa-Sebaste, **28** Küçük Bernaz, **29** Ain Sinu, **30** Hatra (vertical ?), **31** Dura-Europus (vertical ?)

18. Distribution maps of brick barrel vaults (WebCat. 3). A: Sites with radial brick vaults. B: Sites with vertical brick vaults.

19. Remains of cistern vault at Rhodiapolis, Turkey. The section above the impost is laid radially with the holes for the centering beams still visible. In the upper parts the bricks are set vertically with occasional ribs of radial brick. Note that the radial brick ribs do not align with the centering holes.

then subsequent rings were added by "gluing" them with quick-drying mortar, either gypsum or a mud slurry. The brick rings were set at an angle to help prevent them from sliding down before the mortar had set. The method developed in areas where wood was scarce because it provided a way of building vaults without using a wooden centering structure.

With regard to Roman barrel vaults, however, the term *pitched* is problematic because the bricks in most of them are not pitched – they are set vertically (Figs. 17A and 19). The fact that the same term has been used to describe both the vertical and the pitched type has obscured an important distinction that provides clues regarding the transmission of the technique into Roman architecture. It has also led to the assumption that both methods were used for the same reason, which is not necessarily the case. In discussing the development of Roman brick barrel vaulting, I refer to the examples that are set at an angle as *pitched* and those that are not as *vertical* to reflect the difference between the two types.

RADIAL BRICK: EARLY GRAECO-ROMAN EXAMPLES

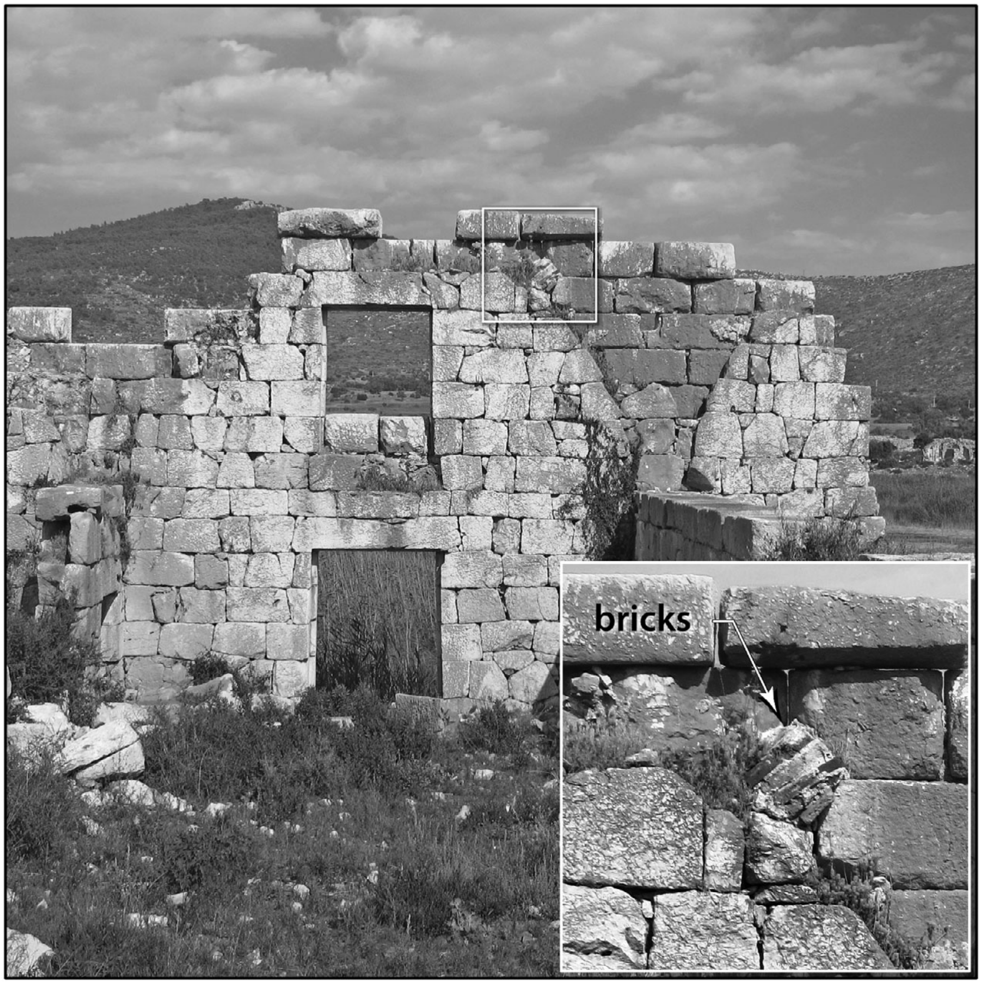
Using bricks instead of stone voussoirs to create a barrel vault does not take a great leap of imagination, nor are very many bricks needed for small tomb chambers (e.g., about 370 for one of the Reggio Calabria vaults supplied by Memnon), which were the earliest applications. As vaults grow larger, the main issue becomes one of supplying the bricks. Because bricks were used in walls before they were employed in vaults, a brief overview of brick construction in the Greek East provides a basis for examining the vaults.

The use of mud brick for walls and fired terracotta tiles for roofs in the Greek world has a long history before the Romans arrived. The earliest terracotta roof tiles can be traced back to the mid-seventh century BCE in both Greece and Italy,[11] whereas fired brick for walling came later. Under Roman rule fired brick was used in the Greek East in two ways: as facing or as a structural material running through the entire thickness of the wall. In Greece, fired brick facing (sometimes combined with *opus reticulatum*) was used under Augustus in the city walls of the new colony at Nicopolis.[12] In Asia Minor, the earliest example is usually cited as the Library of Celsus at Ephesus (113–114 CE), though brick bands occur in the walls of *opus vittatum* (facing of small rectangular stones in regular courses, also known as *petit appareil*) at the Flavian Basilica at Aphrodisias.[13]

As with bricks in walls, brick vaulting was also adopted earlier in Greece than in Asia Minor. P. Vitti has recently documented an early example of a brick vault just outside Patras in the Mausoleum of Marcia Maxima,[14] which has been dated to the early first century CE.[15] Thus far, few other examples datable to the first century have come to light. However, an impressive use of brick vaulting can be seen in the Southwest Baths at Olympia (8 m span), which has been dated to the late first century CE by the excavator.[16] The stadium at Patras employs brick vaults, although both Domitianic and Hadrianic dates have been proposed, and the publication of the evidence from recent excavations is still pending.[17] Thus brick vaulting may have been more common than realized in Greece by the second half of the first century CE, though the lack of dating criteria for many structures makes the frequency of its early use difficult to assess.

The introduction of brick vaulting in Asia Minor appears to have occurred only in the second century CE. It was certainly used by the time of Hadrian when it is found employed for the vaults of the Hadrianic *Horrea* at Patara (Fig. 20, WebFig. 7), which are dated to 129 CE by the dedicatory inscription.[18] Pre-Hadrianic dates have sometimes been attributed to a few other structures with radial brick vaults: the Harbor Baths at Ephesus, the Humeitepe Baths at Miletus, and the Baths of Vespasian at Patara. The dates of the brick vaulting in the latter two are uncertain but are probably mid-second century.[19] The date of the Harbor Baths deserves a closer examination because they are among the largest baths in Asia Minor and have sometimes been dated to the late first century CE.

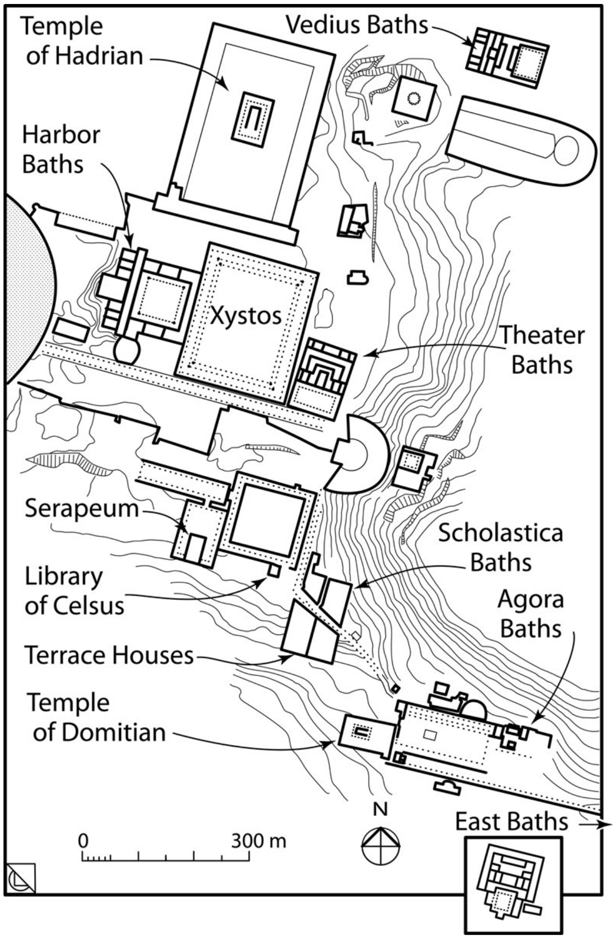
The Harbor Baths belong to a larger complex that has traditionally been dated to the Domitianic period, but the date assigned to the baths themselves has oscillated between the Domitianic and Hadrianic periods.[20] They were built between the harbor and a *palaestra*/gymnasium to the east, which in turn was connected to the Xystos, an enormous three-aisled porticoed structure (Fig. 21). The Domitianic date attributed to both the *palaestra* and the baths was based on a fragmentary inscription in the marble hall of the *palaestra* and on an inscription on a statue base found in the one of the large halls of the baths, both of which have been dated to 92/3 CE.[21] However, U. Quatember has recently questioned the validity of using the *palaestra* inscription as evidence for a Domitianic date because it uses an angular lunate sigma that was not in use during the Flavian period. She also notes that R. Heberdey, the excavator, wrote in his sketchbook that the lettering was not Flavian and that he suspected the inscription was a repair.[22] Moreover, V. M. Strocka examined a capital from the baths in the context of other decorative carving from the late first to the mid-second century CE and proposed a Hadrianic dating, noting that it was nothing like the carving on other Domitianic monuments in Ephesus.[23] Hadrianic work was certainly going on in the area, as demonstrated by the inscription dated to 130/1 CE noting that C. Claudius Verulanus Marcellus and his wife Scaptia Philippe paid for the marble revetment of the "stoas" (those of the Xystos).[24] This work was presumably a remodeling of an older



20. Hadrianic *Horrea* at Patara (129 CE). Inset shows a few radial bricks that remain in the grooves carved into the front wall. (Color image: WebFig. 7).

structure because Heberdey discovered that the floor level had been raised at the time of the renovation, probably because of problems with the water table in this low zone.[25]

Further evidence supporting a Hadrianic date for the Harbor Baths comes from the work on the harbor basin itself. Excavations under the road running along the jetty walls revealed finds dating from 50–125 CE,[26] the latter date thus supplying a *terminus post quem* for their completion, which would have been part of the general land reclamation in this zone for building the baths. Indeed in 1933, Keil comments on the water table problems he encountered when trying to document the substantial substructures that run under the bath building.[27] In 129 CE, Hadrian was honored for having made the harbor navigable, and shortly thereafter, in 131/2 CE, he granted Ephesus its second *neocorate*, which was celebrated by building an enormous temple just north of the Harbor Baths.[28] That the Harbor Baths were associated with the *neocoros* temple is implied both by its location and by a series of inscriptions referring to "Baths of the Emperor(s)," which most likely refer to the Harbor Baths.[29] A Hadrianic date for the



21. Plan of Ephesus, Turkey, showing location of monuments mentioned in the text.

Harbor Baths would make them contemporary with the Hadrianic *Horrea* at Patara and place them squarely within the period when brick production at Ephesus saw a great increase, as evidenced by the use of brick vaults at the other second-century bath complexes in Ephesus (Vedius, Theater, East). A Domitianic date, in contrast, would make them a chronological outlier in the use of brick vaulting both at Ephesus and in Asia Minor in general.

RADIAL BRICK: PURPOSE

The fact that the builders in Rome chose to reinforce their concrete vaults at points of stress with radially laid bricks suggests that they saw them as structurally superior to vaults of *opus caementicium*. Examples occur at the Colosseum, Trajan's Markets, the Pantheon, and the Baths of Caracalla, to name a few.[30] J. DeLaine, in her study of the Baths of Caracalla, points out that an advantage of employing radially laid brick is that proportionally less mortar is used than in regular *opus caementicium* vault construction, so the strength of the vault is less dependent on the curing of the mortar and construction could proceed more quickly.[31] Using bricks as voussoirs minimized the amount of mortar between the units and also regularized the mortar joints, enabling a more even transfer of forces from one brick to the next. In other words, the vault would behave more like a cut stone voussoir vault. This reasoning would apply equally to brick vaulted construction in the provinces where the mortar did not usually have the highly pozzolanic properties of the mortars in Rome.

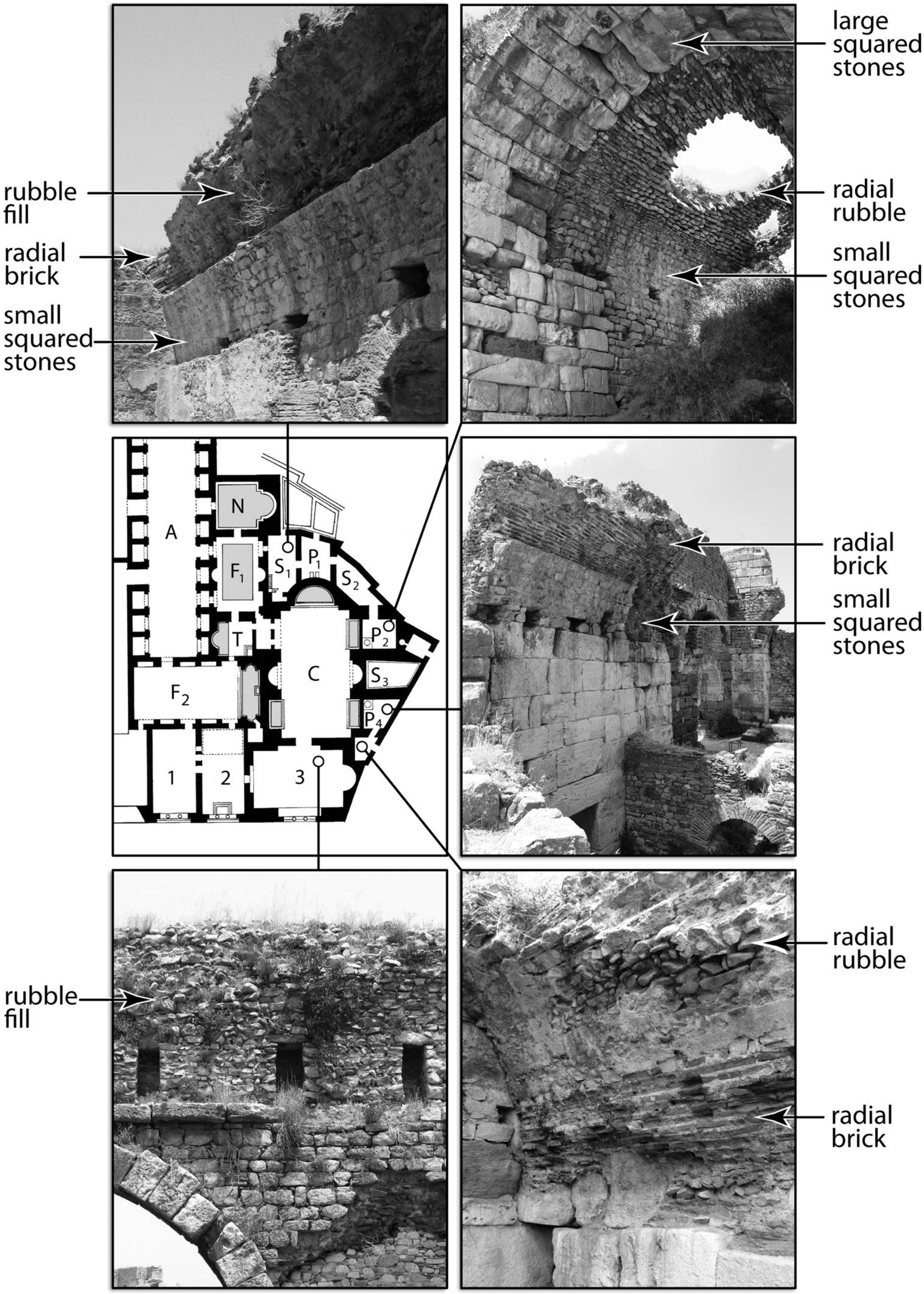
Another potential advantage of bricks over both radially laid rubble and cut stone voussoirs is that they are typically lighter than many of the stones used. Bricks in Rome, which often have lightweight volcanic material as temper, weigh between 1,550 and 1,750 kg/m^3. Terracotta with denser temper may weigh as much as 2,000 kg/m^3, but the weight of limestone, shale, and marble is around 2,600 kg/m^3. A brick vault forms an intrados shell that supports a mortared rubble fill over the haunches. The heavier fill at the sides aids in transferring the lateral thrusts down vertically through the walls, whereas the brick shell lightens the crown. So, particularly for larger vaults, bricks offer advantages in both weight and strength over radially laid mortared rubble. In comparison to cut stone vaults, they have the additional advantage of ease of manufacture via mass production.

The selective use of brick vaulting is illustrated in a number of impressive structures in western Asia Minor. The Baths of Vedius (147–149 CE) at

Ephesus were constructed on a platform made up of radially laid, mortared rubble barrel vaults, whereas the largest vaults of the superstructure were built of brick. The superstructure vaults are not preserved, but some fallen pieces of the brick vaulting were found in excavation of the *natatio* (swimming pool; 9 m span) and the *caldarium* (14 m span).[32] A similar strategy was used at Pergamum. The round Temple of Asclepius was built above vaulted substructures of mortared rubble, whereas the cella was topped by a dome built with bricks (c. 24 m int. dia.). Much of the substructure survives with its annular barrel vaults of radially laid mortared rubble (Fig. 14B). The dome itself no longer exists, but fallen chunks are illustrated in archival photographs that show that at least parts of it were built of very large bricks (c. 96 cm square and 6–7 cm thick).[33] The choice to use bricks for the dome suggests that the builders believed they provided some advantage over radially laid rubble. Moreover, the large size of the bricks suggests that they were specially made for this project. Another advantage offered by bricks for large spanned structures is that the thickness of the shell can be easily controlled either by using larger bricks or multiple rings of bricks. As discussed in Chapter 1, the larger the span, the thicker the shell needed to be to maintain stability.

The Baths of Faustina at Miletus demonstrate that a variety of materials and techniques could be employed within the same structure (Fig. 22, WebFig. 8). In the large *caldarium* (rm C, 13.5 m span), none of the main vault remains, except for chunks of fallen brick vaulting found in the excavations.[34] The *caldarium* to the south (rm 3, 11.3 m span) preserves only the fill, but the shell was likely brick as well. The *praefurnia* along the east of *caldarium* C use a variety of materials, though in each case the haunch is built differently from the crown. In his study of vaults in the Peloponnese, P. Vitti has detected evidence implying that the lower parts of vaults were often built separately from the upper parts. The point of change is sometimes marked either by a construction joint (mausoleum RG1 at Troezen) or by a change in material. The lower vertical zone could be built without centering, which would then be added to complete the upper parts.[35] A similar explanation could apply to these vaults at the Baths of Faustina. The haunch was always built of shaped stones or bricks that could be built up without centering, and then the unformed stones or the bricks, whichever were available, were used in the upper parts. The bricks and unshaped flat stones also offered the advantage of being employed in small-scale units that could be handled by workmen without the need for lifting equipment.

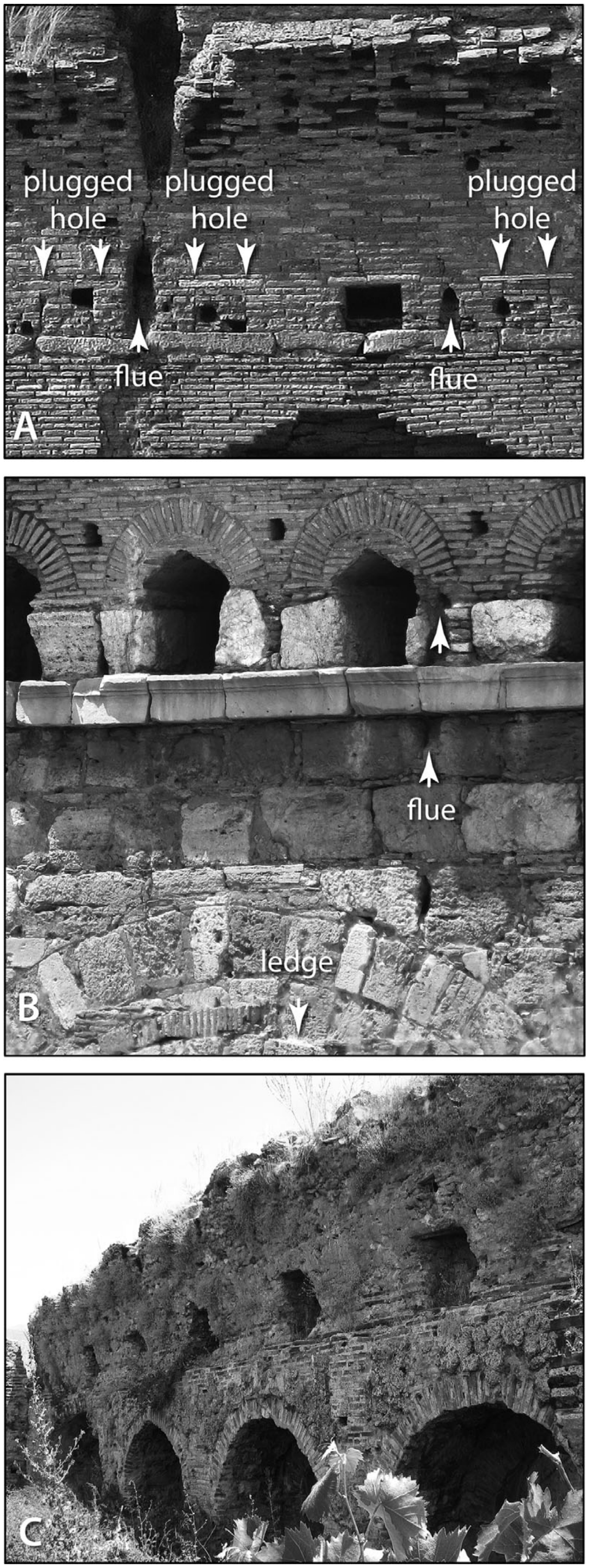
One characteristic of some large brick barrel vaults is that they have sizable centering holes, such as the Southwest Baths at Olympia (8 m span, holes 6–7 brick courses high) and the Brick Baths at Myra (11 m span, holes 7 brick courses high = 65 cm) (Fig. 23C). The most notable are those at the East Baths at Ephesus (14.5 m span, holes 8 brick courses high) (Fig. 23A, WebFig. 9) and at the Uç Goz Baths at Tralles (c. 14 m span, holes 10–12 brick courses high), the latter of which were topped by brick arches (Fig. 23B, WebFig. 10). The only example that I have been able to measure is at Myra, which is 65 cm high and 48 cm wide; those at Ephesus, Tralles, and Miletus (Fig. 22) are even larger. As a comparison, the size of the tie beams recorded for one of the largest documented trusses at the fourth-century basilica of St. Paul's Outside the Walls were 50 × 39 cm,[36] and the largest beam mentioned by Pliny the Elder is the beam of fir from the Diribitorium roof, which was 44 cm square (1.5 RF).[37] These centering holes are therefore much larger than the largest recorded beams. Assuming that they were in fact used for beams of some sort, the size of the holes may have been intended to allow room for manipulating beams into and out of them and possibly to use wedges for raising and lowering the centering.[38] The holes were clearly used only during



22. Baths of Faustina at Miletus, Turkey (mid-second century CE). Photos showing variety of methods of vault construction using both brick and stone. In *caldarium* 3 (lower left) the large centering holes are 125 (h) × 45 (w) × 60 (d) cm (Gerkan and Krischen 1928: 85). (Color image: WebFig. 8).

the construction process because examples at the East Baths at Ephesus (Fig. 23A) and the "Baths of Nero" at Olympia were filled after use.[39]

Cut stone construction was a perfectly viable alternative to brick construction for building large vaults, as demonstrated by the barrel vaults of the Museum Baths at Hierapolis in Turkey (16 m span) and those of the East Baths at Jerash (ancient Gerasa) in Jordan (11.8 m span). These are both places that had strong stone carving traditions and little other use of brick. Hierapolis is the site of the famous thermal springs of Pamukkale with its pillows of travertine accretions and had abundant resources of both limestone and marble. The importance of stone working in the area is documented in a limestone sarcophagus lid (third century CE) of M. Aurelius Ammianos, which depicts a complex, water-driven stone saw and notes that Ammianos was as "skillful as Daedalus in wheel-working."[40] Although no association of stone workers is attested at Hierapolis, the use of the water-powered stone saw illustrates the importance of stone working in the area. The stone carvers in such places must have wielded some political and economic power, which may be one reason for the lack of brick employed. Other reasons for choosing brick over stone could include the availability of the clay and fuel for brick production and the existence of infrastructure for the production and firing of other items. The distribution map (Fig. 18A)



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23. Examples of large beam holes at the base of radial brick barrel vaults. A: East Baths at Ephesus, Turkey (mid-second century CE). The original beam holes were covered by a brick *bipedalis*. Arrows indicate the holes that were later filled and the vertical exhaust flue that ran through the vault. B: Uç Goz Baths at Tralles, Turkey. The beam holes were unusually well constructed with the opening protected by a relieving arch above. Arrows indicate the remains of the exhaust flue and one of the holes carved into the cornice through which the flue ran. Note also the projecting ledge around the arch that provided space for the wall heating, which was vented through the flues in the vault. C: Brick Baths at Myra, Turkey. (Color images: WebFigs. 9–10).

shows that the main places in which brick vaults were employed were along coasts and river valleys where alluvial clays would have been available.

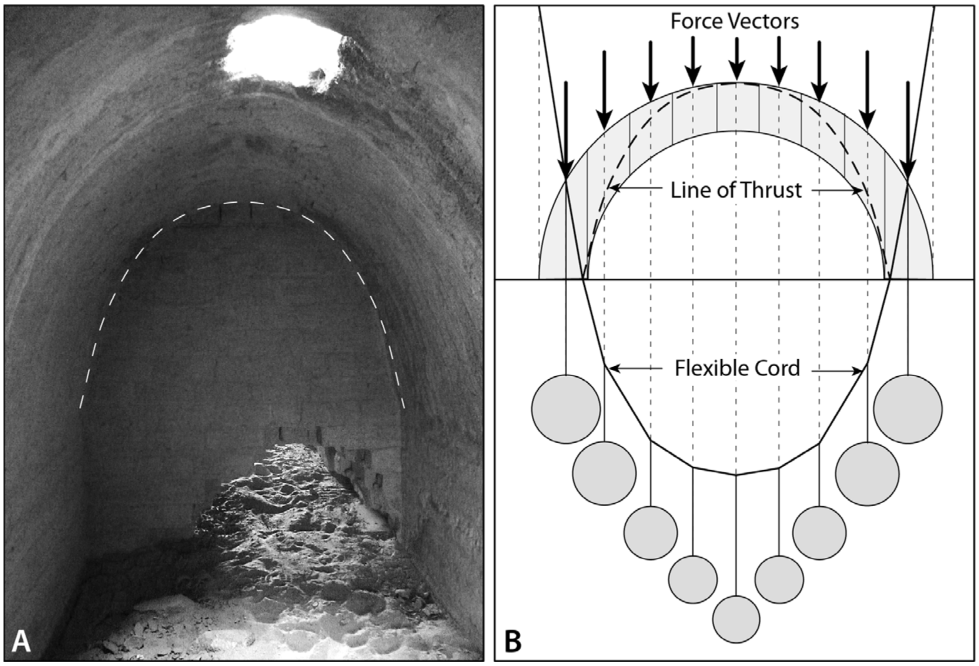
PITCHED MUD BRICK: PRE-ROMAN DEVELOPMENTS

A unique contribution of Roman architecture to vaulting technology was the use of vertical brick vaulting, which was a variation on the age-old eastern practice of pitched mud brick vaulting. In the Roman world, one place where pitched brick vaulting continued to be employed was Roman Egypt, where examples are particularly well preserved in the Fayum, as at Karanis, Bacchias, Soknopaiou Nesos, and Tebtunis.[41] Among the earliest ones at Karanis (the best documented of the Fayum towns) are those in Granary C123, which are dated by papyri and coins to the mid-first century CE.[42] Grain is highly flammable so the typical palm beam ceiling construction used in domestic architecture would not have been practical. Pitched mud brick vaulting was also used extensively for the underground storerooms of houses in the Fayum.

Pitched mud brick was clearly indigenous to Egypt going back as far the middle of the third millennium BCE, as indicated by the Mastaba el-Faraoun in Saqqara, the burial place of the pharaoh Shepseskaf, where the technique was used to cover a passageway (1.7 m span).[43] The most famous pharaonic examples occur in the warehouses of the Ramesseum in Thebes (c. 3.5 m span; thirteenth century BCE). The bricks used were typically smaller, thinner, and lighter than those used for wall bricks because they had to be held in place by the suction of the mud mortar without sliding off. They often bear finger grooves applied before drying, which served to prevent slippage.[44] The fired bricks used by the Romans in their vertical brick vaulting were typically thinner than normal bricks for the same reason.[45]

The Roman barrel vaults of the Fayum follow their pharaonic predecessors in taking an elongated curvilinear form rather than a semicircular one (Fig. 24A). The form has been described using various geometric terms: *parabolic*, *semi oval*, or *catenary*.[46] In reality, the precise geometry for these elongated vaults is inconsequential because the form in most cases was simply derived from the initial construction process, rather than having any theoretical basis.[47] In the early examples of vaulting with stone, the builders began by corbeling the lower part of the vault inward to reduce the span and then capped it with an arch, so that the result was a high tapering arched form. Similar elongated forms were also used for vaults of pitched brick. Because the point of the pitched brick technique was to build without centering, the final geometric form was typically not the foremost concern. However, pharaonic builders also built semicircular vaults in both stone and pitched brick when this form was desired, as in the elegantly painted Tomb of Sennedjem at Dier el Medina (2.6 m) (Fig. 25).[48] Significantly, the largest brick vault (7.70 m span) known from pharaonic Egypt was semicircular and the bricks were pitched. Appropriately it occurred at Thebes in the tomb of Amenhotep, son of Hapu, who was the architect of Pharaoh Amenhotep III (fourteenth century BCE).[49] Making the vault semicircular would actually require more care in laying out the form, so it is not surprising that the larger or more highly decorated tombs would have vaults with semicircular profiles.

Even if the elongated arch form had little theoretical basis, it did offer structural advantages of which the builders must have been generally aware. In 1679 Robert Hooke famously stated "As hangs the flexible line, so but inverted will stand the rigid arch."[50] In other words, if one takes a flexible line and hangs from it weights equivalent to the weights of the sections of a comparable standing arch, the line takes the form of a curve, which, in turn, if made rigid



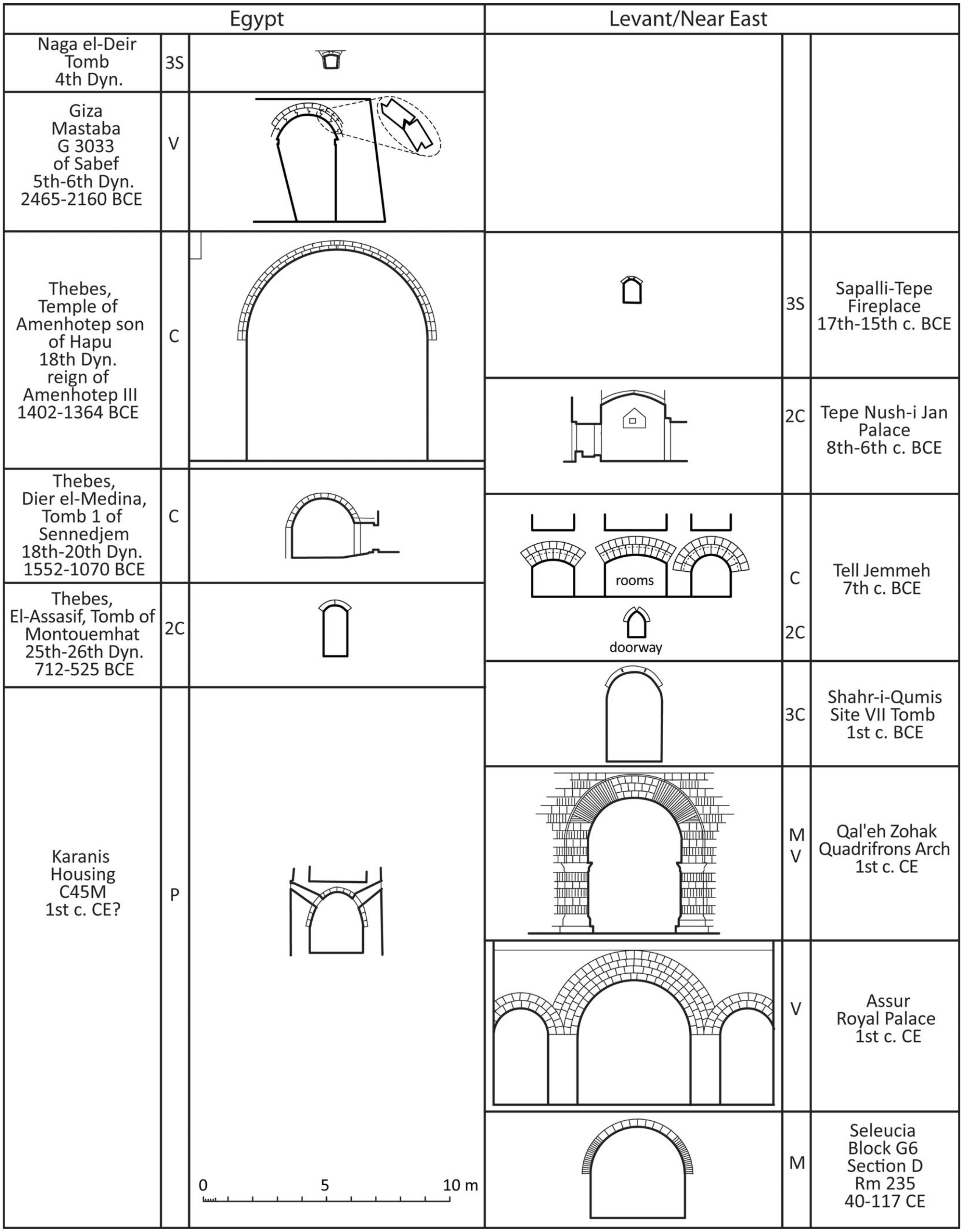
24. A: Roman pitched mud brick vault from a house at Soknopaiou Nesos in the Fayum, Egypt, showing an elongated profile (photo: Stefano Camporeale). B: Diagram of Hooke's principle – "As hangs the flexible line, so but inverted will stand the rigid arch" – thus illustrating the structural efficiency of the elongated arch forms in the Fayum.

and flipped upright, represents the ideal shape of the arch capable of carrying those loads in compression (Fig. 24B) (i.e., a catenary curve).[51] As in pharaonic Egypt, the elongated arch form developed early in the Near East for the same constructional reasons, but there it was not relegated to underground tombs and substructures, and it became a distinctive design feature, which was immortalized in the sixth-century CE arch (25.65 m span) of the Sassanid palace at Ctesiphon in Iraq.[52] In modern times the principle was applied in Eero Saarinen's Gateway Arch in St. Louis (193 m span), which is a precisely calculated catenary arch. Such elongated arch forms were evidently not as pleasing to the Graeco-Roman sensibilities and rarely appear in Roman architecture outside of Egypt.[53]

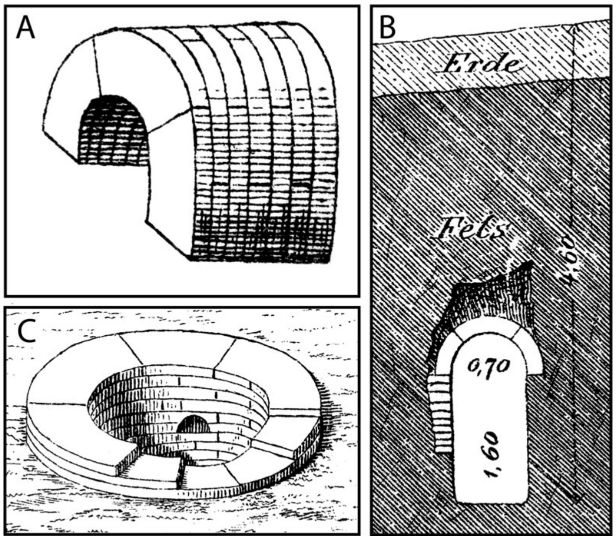
VERTICAL BRICK: EARLY EXAMPLES

When the idea of setting bricks on edge was applied to Roman barrel vaults outside of Egypt, the bricks were set vertically instead of pitched, and the form of the vault was either semicircular or a shallower arc segment.[54] The distribution map (Fig. 18B) shows that vertical brick vaults are limited to Greece and Asia Minor, with the earliest datable ones appearing in central Greece. Though clearly derived from pitched mud brick vaulting in the East, the Roman application of setting bricks on edge displays unique characteristics that make it particularly useful for exploring modes of technology transfer. By examining when and where the technique was first used in Roman architecture and how it was used, one can gain a better understanding of the way in which interactions between cultures affected its adoption and diffusion.

The first securely dated vertical brick vaults occur in Athens in the aqueduct that was installed by Hadrian and dedicated by Antoninus Pius in 140 CE, two years after Hadrian's death.[55] The vaults



25. Chart comparing the development of vault forms and sizes in Egypt and the Levant/Near East. The letter/number codes are as follows: 3S, three straight bricks; V, vertical bricks; C, curved bricks; 2C, two curved bricks; 3C, three curved bricks; M, mixed radial and vertical bricks; P, pitched bricks.



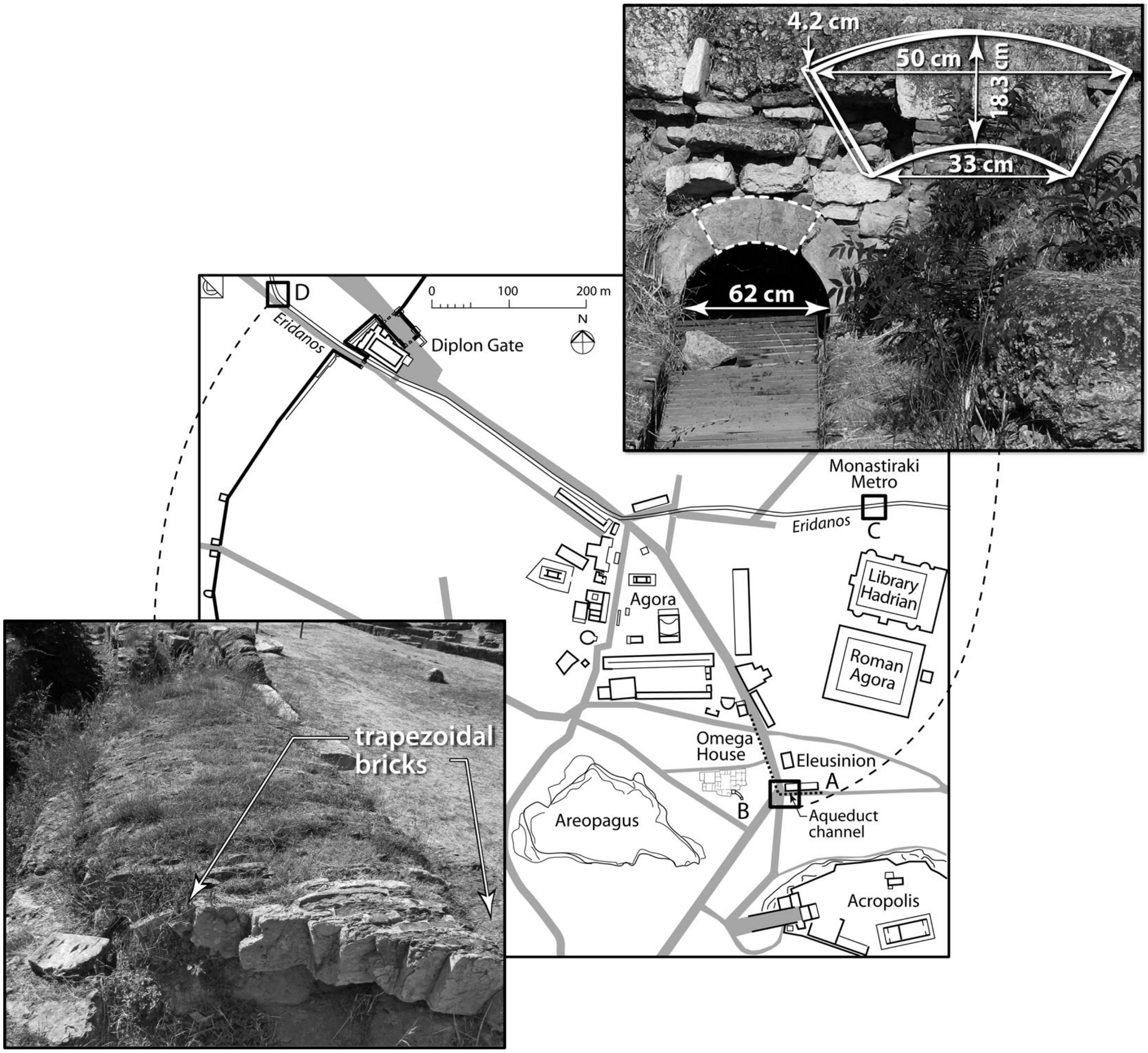
26. Aqueduct of Hadrian at Athens, Greece. E. Ziller's drawings of the use of prefabricated curved bricks to form the vaults of underground channels as well as *puteus* shafts (Ziller 1877: Taf. 8). A: Configuration of vault made with three curved bricks. B: Underground aqueduct channel with three-brick vault. C: Circular *puteus* made with six curved bricks.

covering some sections of the aqueduct channel (60–70 cm span) were built of specially made curved, fired bricks so that three of them together created a semicircular arch (Fig. 26). The most important example for dating comes from a section outside the city where the channel runs underground because it can be securely attributed to the original Hadrianic project. Most of the underground sections of the channel were carved out of the rock, but one part passed through a layer of clay, so the three-brick method was used for its vaulting. The vertical air vents (*putei*) typical of Roman aqueducts were constructed in the same manner using six of the bricks to create a circular shaft (Fig. 26).[56]

Other examples of the three-brick vaulted channels were used in Athens to house the pressurized pipes of the water distribution system. One is still visible running behind the south stoa of the City Eleusinion (Fig. 27).[57] Nearby, another example occurs in Omega House (Agora grid Q21) on the northeast slope of the Areopagus. It covers a 10 m long tunnel (1.10 m span) that led from a springhouse back into the hillside to a rock-cut well/cistern. Finds in a secondary well shaft show that the system dates to the first half of the second century and is likely contemporary with the aqueduct project.[58] A different type of vertical brick vault enclosed sections of the Eridanos river channel. One section of remaining vault (1.7 m span) runs to the south of Hagia Triada in the Ceramicus (Fig. 27). Another section was found during excavations for the Monastiraki Metro station and dated to the Hadrianic period. Both were constructed using trapezoidal bricks (imitating voussoirs) specially made for vertical brick vaulting.[59]

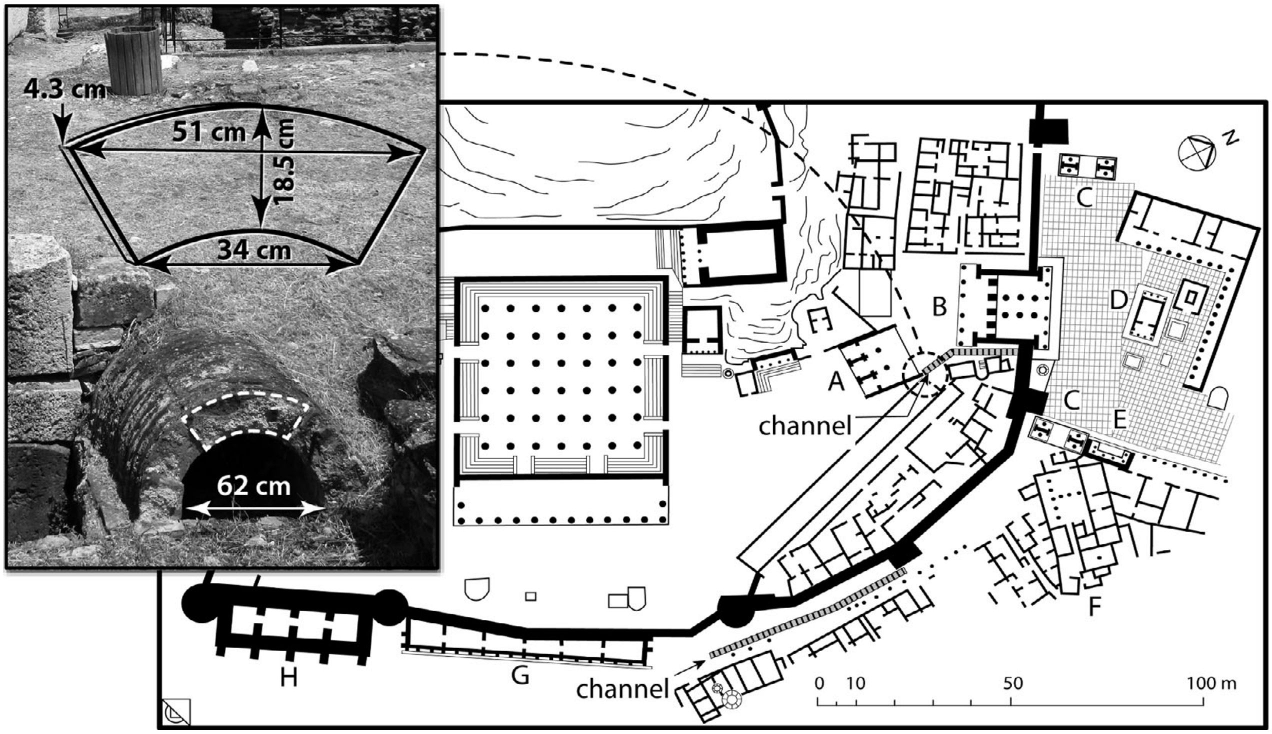
The same type of three-brick vault used in Athens was also used in the water supply system at the Sanctuary of Demeter at Eleusis, 20 km to the west. The brick vaulted channels occur within the sanctuary itself and along the ancient road that runs outside the east fortification walls (Fig. 28). The aqueduct at Eleusis is not as clearly dated as the one in Athens, but it has generally been assumed to be Hadrianic.[60] It must have been built by 160 CE when Pausanias visited the sanctuary and saw the little Temple of Artemis (Fig. 28), which is part of the same construction phase as the nearby fountain supplied by the aqueduct.[61] The bricks used at Eleusis are the same size as those in Athens, suggesting that production for both projects may have been coordinated (compare Figs. 27 (upper inset), 28 (inset)).

A related variation of the same vaulting method occurs in the drainage system at Argos. Given the location at the base of the Larissa hill, the agora was often subject to torrents of runoff that from the fifth century BCE were controlled by a series of large drainage channels running under it (Fig. 29). As at Athens, Argos acquired some upgrades in its drainage and water supply under Hadrian. The most famous is the north aqueduct, which ends in the Larissa *nympheum*, where a naked statue of Hadrian



27. Map of Athens, Greece in the second century CE: A, aqueduct channel behind south stoa at the City Eleusinion (upper inset photo); B, second-century CE fountain house in the fourth-century CE Omega House; C, vault over Eridanos River under Monastiriki Metro station; D, vault over Eridanos River in the Ceramicus (lower inset photo).

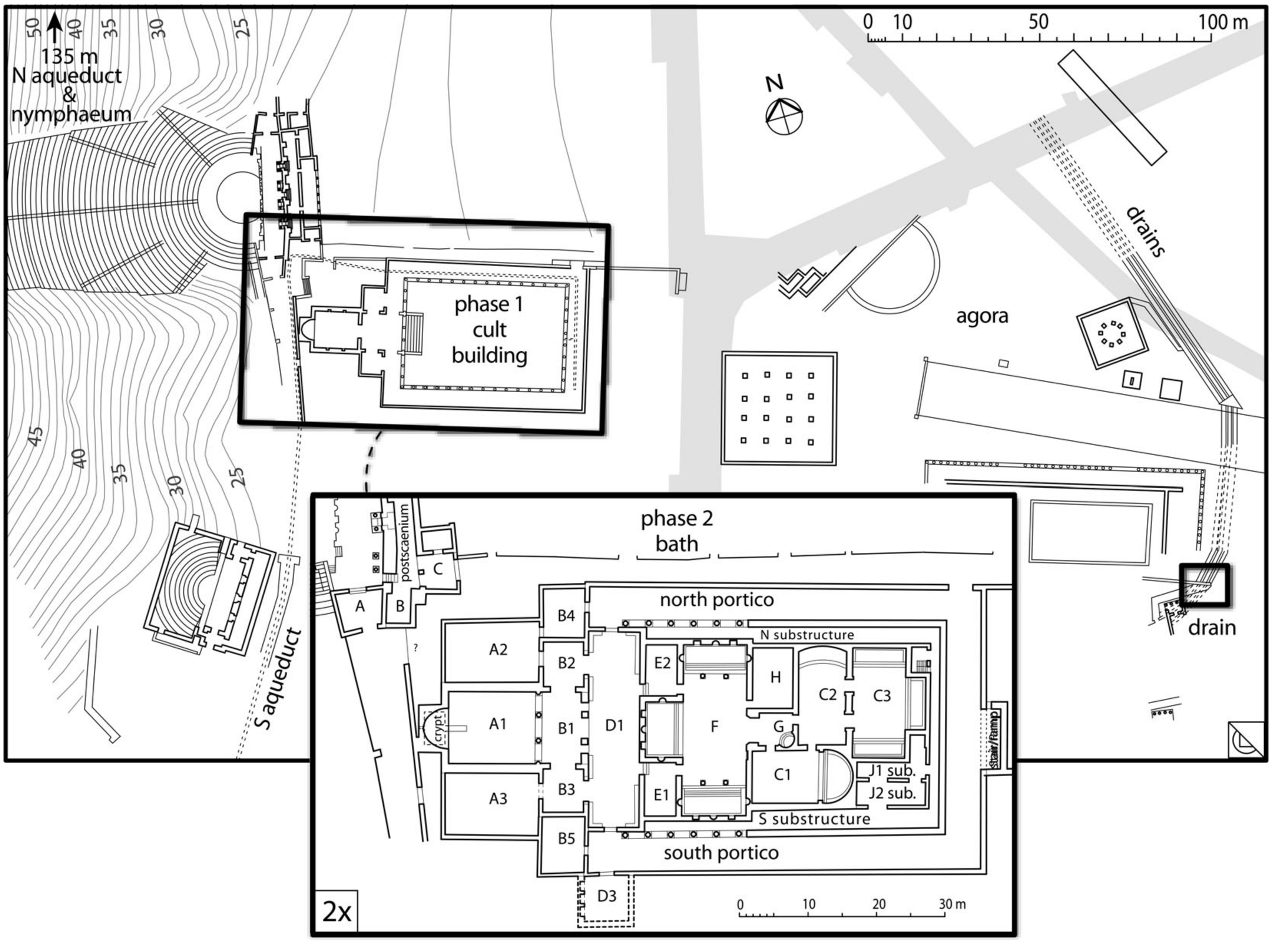
was found.[62] Lesser known is the south aqueduct, which probably dates to the same time.[63] As part of the development of this infrastructure, some of the agora drains were rerouted and rebuilt with brick vaults, one of which was excavated with the vault (1.20 m span) still intact. It was built with radial bricks at the haunch and vertical ones at the crown (Fig. 30). This work was also dated to the Hadrianic period by a denarius of 119 CE and Hadrianic pottery found in another section of one of the remodeled drains (no vaults were preserved).[64] Thus, in Athens, Eleusis, and Argos a number of variations on the vertical brick



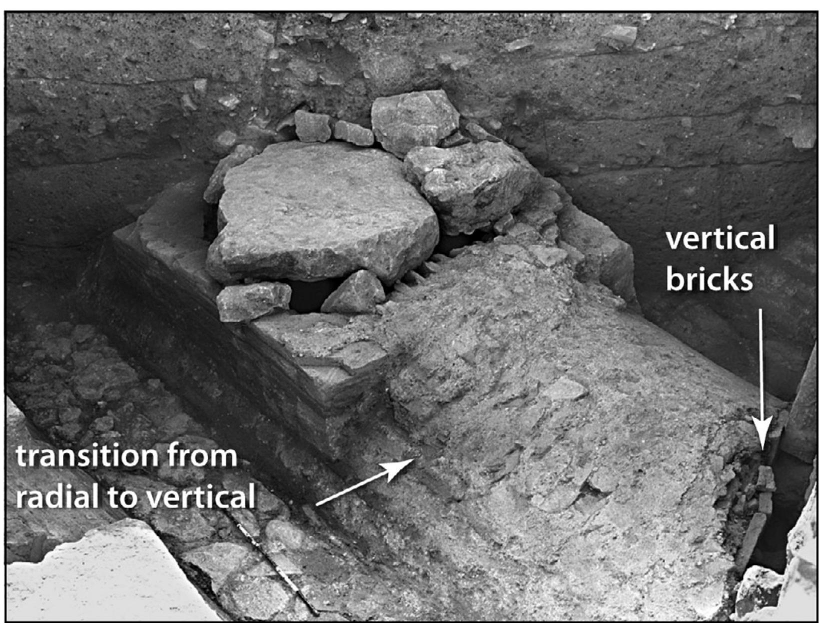
28. Plan of Roman Eleusis indicating locations of three-brick channels (inset photo). Labeled structures: A, Lesser Propylaea; B, Greater Propylaea; C, monumental arches; D, Temple of Artemis; E, forecourt fountains; F, Roman bath; G, fountain; and H, cisterns.

vaulting technique were being used for infrastructure improvement projects relating to water control under Hadrian.

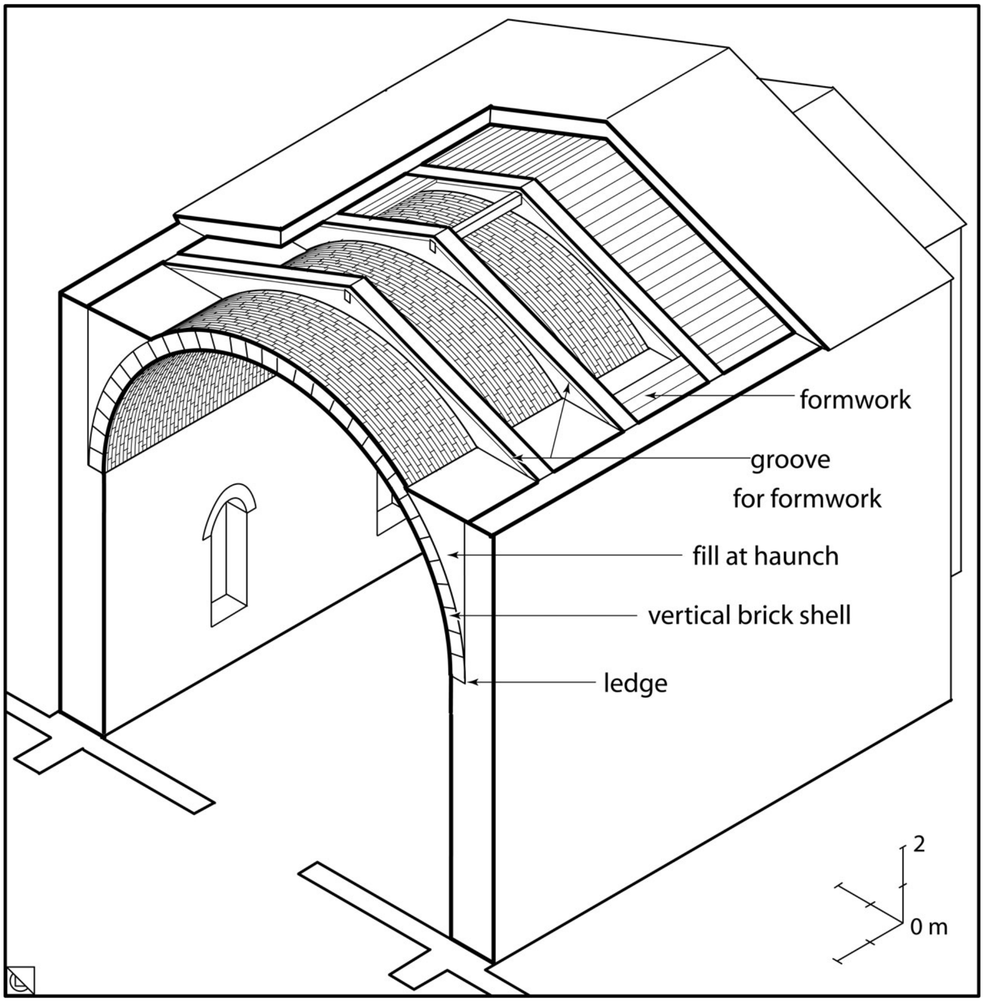
All of the vaults discussed so far are innovative in the manner in which the bricks are formed and set into place, but they are not impressively large; however, one of the more extraordinary vaulted structures discussed in this study occurs at Argos in the cult complex adjacent to the agora. The main cult room A1 was covered by a freestanding barrel vault (10.7 m span) built entirely of vertical bricks (Fig. 31). The complex, consisting of two phases, is often referred to as the "Serapeum" or the "Theater Baths" or simply "Bath A." The first phase included the main cult room (A1), which faced onto a sunken porticoed courtyard (Fig. 29). An apse on the back wall of A1 held the cult statue, and it had a vaulted crypt below, also built using vertical bricks. In a second phase, the sunken courtyard was filled with a bath building (Fig. 29 inset). The excavator, P. Aupert, dated the original structure to the early Trajanic period around 100 CE and argued that it was originally a temple for the Egyptian god Serapis. He dated the second-phase addition of the bath to the Hadrianic period based on fragments of an imperial inscription found lying in its substructure.[65] However, in a 2010 article, I argue for the original complex being built under Hadrian (probably for the Greek god Asclepius), with the bath being added later in the second century. I base the revised dating on pottery finds in the trenches that do not occur before the Hadrianic period and on the relationship between walls in the cult complex, the adjacent theater, and the south aqueduct.[66] I believe that this later dating is important for understanding why such an unusual structure would appear when and where it did.



29. Plan of Argos with original layout of cult complex near the agora. Inset: plan of second phase of cult complex with bath addition (Theater Baths).

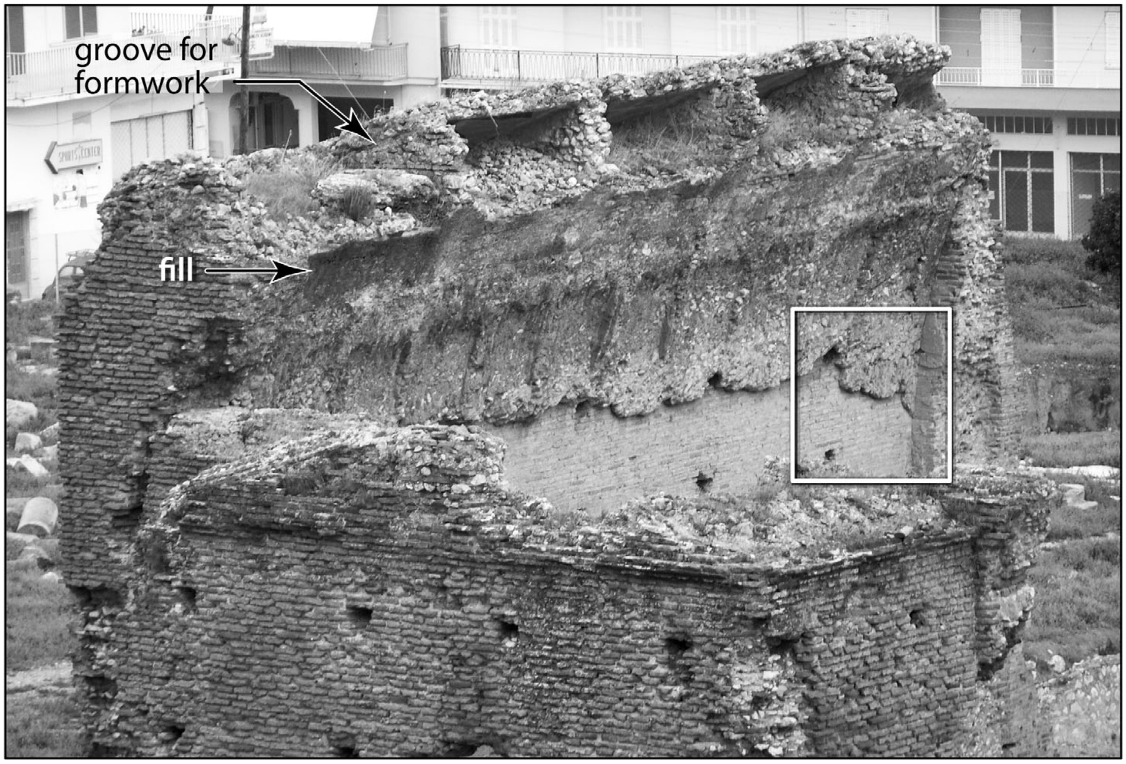


30. Argos, Greece. Photo of second-century drain in the agora showing the crown of the vault built of vertical bricks (Feissel 1978: fig. 32). (© École française d'Athènes).

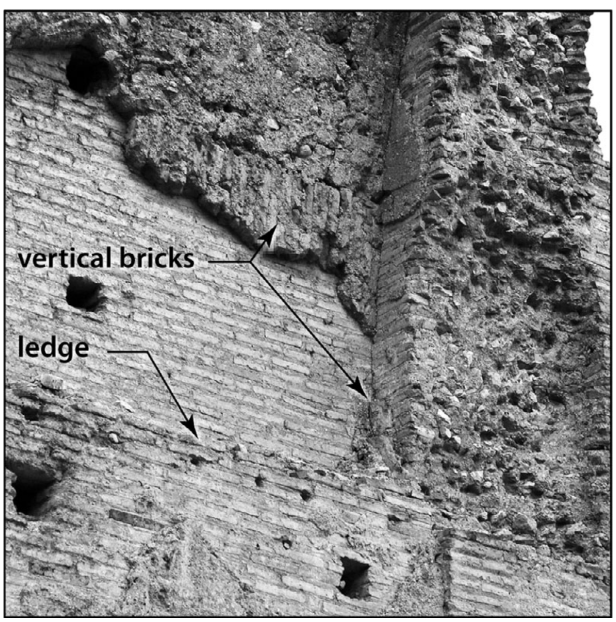


31. Cult complex (Theater Baths) at Argos, Greece. Author's reconstruction of the roof construction of the main cult room (A1).

The roofing system of the main cult room A1 is unique in Roman architecture.[67] It consisted of a double shell, of which the vertical brick vault forms the inner one (41 cm thick) (Fig. 31). Most of the bricks have been robbed, but some traces remain in the northeast corner (Figs. 32–33). I have not been able to examine these traces up close, but the barrel vault of the crypt under the apse (4.2 m span) was built in a similar technique, and enough survives to indicate that the bricks are slightly trapezoidal (24.5–25.5 cm on the shorter side and 28 cm on the longer side, 41 cm tall, and 5 cm thick) and thus specially made for vaulting. The vertical brick shell of the main vault sprang from setbacks built into the two supporting walls, and the area above its haunches was filled with mortared rubble, which is the part visible today (Fig. 32). A series of four parallel walls were built on top of the fill and against the protruding upper part of the brick shell. At the top of each wall is a recessed groove that once held the wooden formwork on which the outer concrete gable was built. These wooden boards, the imprints of which are visible, supported the outer shell of *opus caementicium* and formed hollow spaces between the inner and



32. Cult complex (Theater Baths) at Argos Greece. Photo of cult room A1 from above showing the hollow roof structure. White box indicates location of detail in Figure 33.



33. Cult complex (Theater Baths) at Argos, Greece. Detail of Figure 32 showing remaining vertical bricks.

outer shells. The spaces served to reduce the weight of the roof structure bearing on the walls. The final structure had a barrel-vaulted interior with a traditional looking gabled exterior. For all its inventiveness and technological prowess it was never imitated. The effect of the unusual construction method on the structural behavior of this vaulted room is explored further in Chapter 8.

VERTICAL BRICK: DIFFUSION

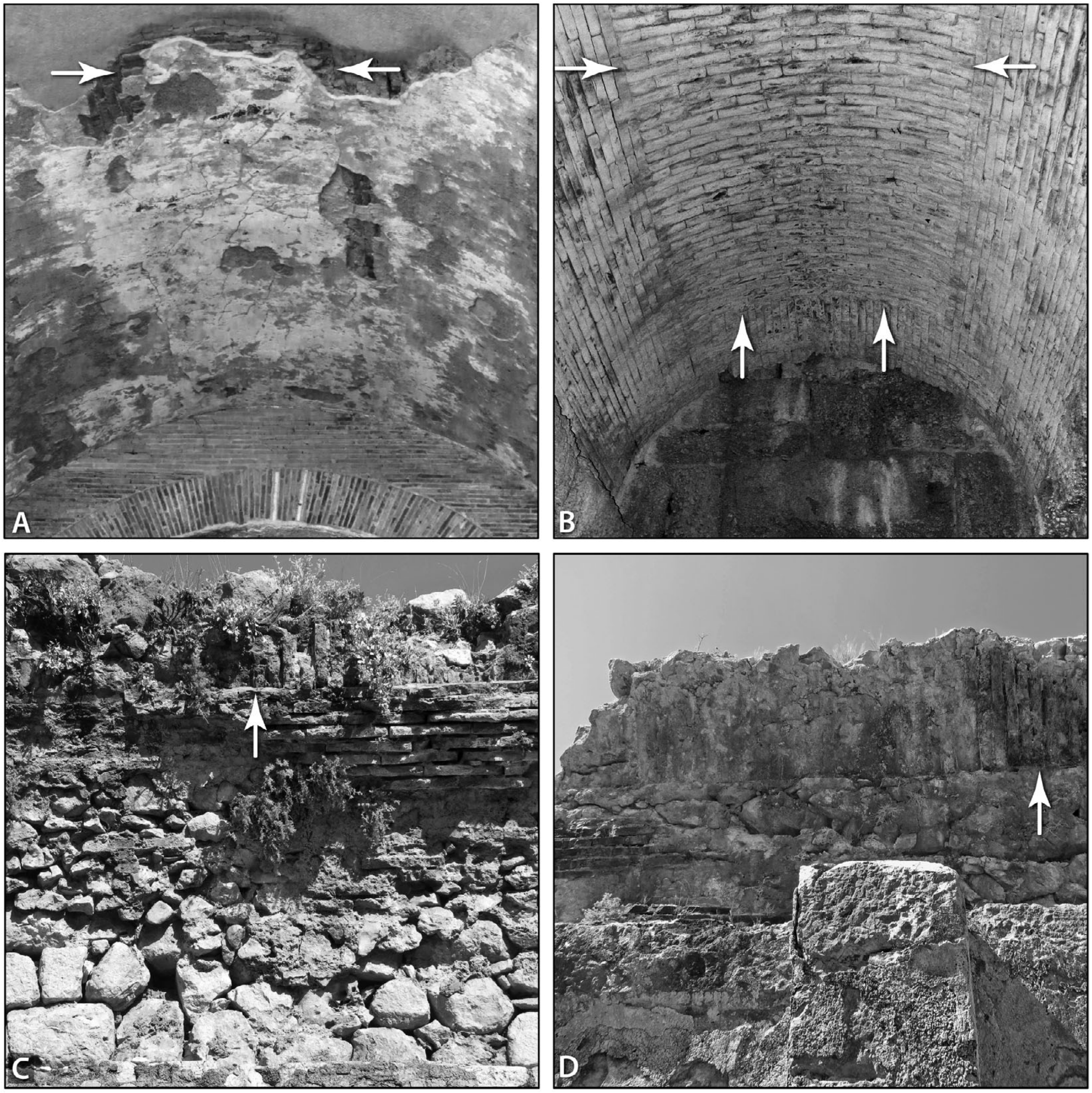
Vertical brick barrel vaults continued to be built in mainland Greece (WebCat. 3-B), as can be seen in a Roman bath near Loutsa in Messenia, in the "Baths of Nero" (also known as the East Baths, first half of third century CE) at Olympia, and northward to Dion in ancient Macedonia where they were used in an aqueduct channel and cistern.[68] They also spread to the island of Crete, where there are at least seven examples, including one at Gortyn in an aqueduct channel built with the same three-brick method as at Athens and Eleusis.[69] In Asia Minor, the use of vertical brick barrel vaulting began to appear along the western and southern coasts around the mid-second century (Fig. 18B, WebCat. 3-B). Thus far the earliest datable example comes from the Baths of Vedius at Ephesus (147–149 CE) where excavators found a fallen piece from the *caldarium* (14 m span), revealing that it had a crown of vertical brick vaulting. Trapezoidal bricks found in the *natatio* (9 m span) suggest that the same technique was used there.[70] Also in the mid-second century at Ephesus the vault of the large "basilica" room 8 (8 m span) in Residential Unit 6 (RU6) of Terrace House 2 was built with a crown of vertical bricks (Fig. 34A).[71] Other second-century examples with less firmly established dates are found at Samos in the *tepidarium* of the baths (12.75 m span) and at Patara in the Baths of Vespasian (11.8 m span) and in the Southwest Baths (11.2 m span) (Figs. 34C–D, WebFigs. 11–12).[72] The most commonly cited example occurs in the substructures of the basilica at Aspendus (3.35 m span, late second or third century (?); Fig. 34B).[73]

Vertical brick construction was most often used only at the crown of vaults, which is rarely preserved, so identifying its presence in partially preserved vaults is difficult, if not impossible, unless the fallen parts are excavated, as at the Baths of Vedius at Ephesus. The Baths of Vespasian at Patara illustrates the problem. In the westernmost room (added in a second phase) most of the brick shell forming the intrados is missing; the only indication of the construction comes from a small remaining patch of vertical bricks high up on the haunch, above courses of radially laid brick. Only a very close inspection reveals the few vertical bricks that remain (Fig. 34C, WebFig. 11). Without those bricks, one would assume that the whole vault consisted of radial construction. Another example where identification is only possible by close observation is at Baths III.2.b at Anamurium (mid-third century CE). Most of the brick shells on which the mortared rubble fill was laid are now missing, but the impressions of the vertical bricks are visible in the mortared fill (WebFig. 13).[74] These baths, along with the Agora Baths at Side (WebFig. 14), were unusual in having the entire vault built of vertical bricks (as opposed to at the crown only).

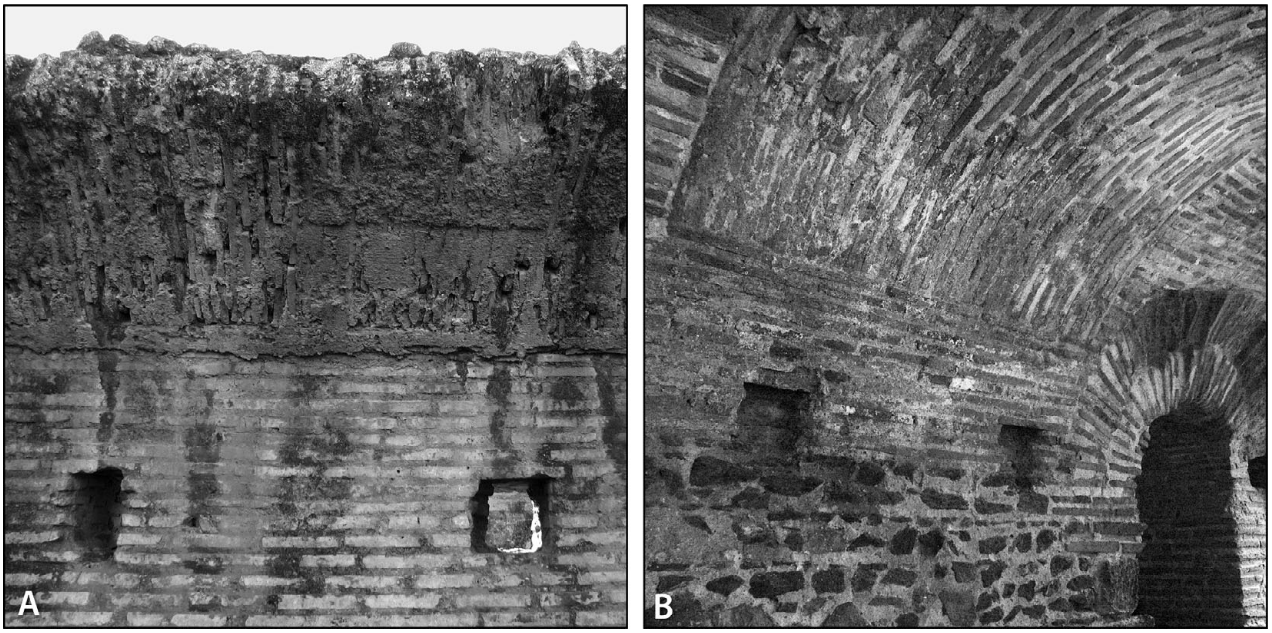
VERTICAL BRICK: PURPOSE

The most obvious reason for using the three-brick method for building small drainage and aqueduct channels was to eliminate the need for wooden centering. In open-air situations, the two side bricks could be mortared to the preceding ring and then the top brick inserted from above, as with a keystone. For such small arch rings, quick-drying gypsum mortar was not necessary; a normal lime mortar would have enough viscosity to hold the bricks in place long enough to set them up. For the underground tunneling, the technique allowed for the pieces be set up from below as the tunnel was being cut, with the top piece inserted from the front, much as miners today work. C. F. Giuliani's investigation of the construction of the Emissarium at Alba Fucens demonstrates the difficulties of tunnel building that required concrete vaulting in unstable ground conditions.[75] By using the three-brick arches for the underground aqueduct channel outside Athens, the builders could construct it from below without centering as it was being excavated, and the same type of bricks then formed the circular ventilation shafts. It was a clever solution to a difficult constructional situation.

The reason for using the vertical bricks at the crown of the vault when the haunches are built of radial brick is not always clear. A. Choisy, in his 1883 monograph on Byzantine construction, discussed this type of hybrid construction and explained that the



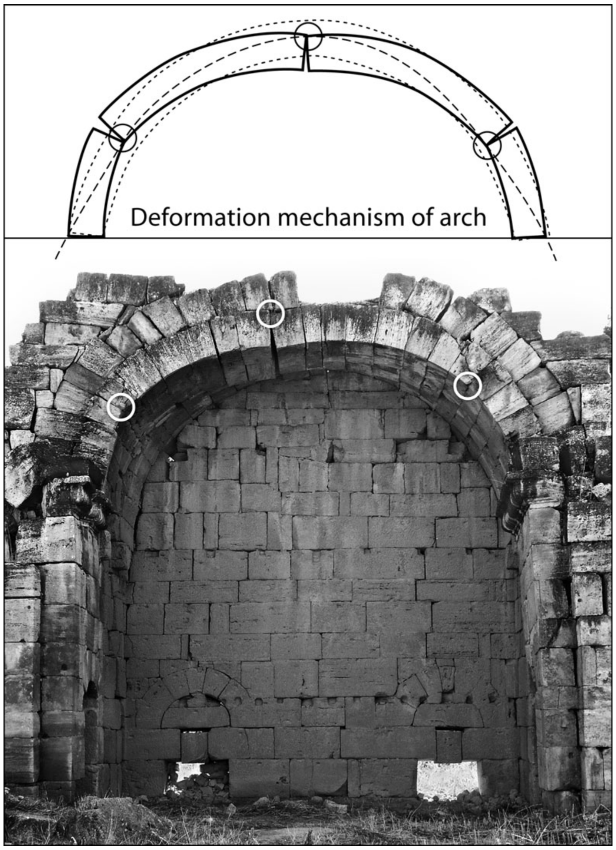
34. Examples of vaults with the mixed use of radial bricks at the haunch and vertical bricks at the crown. Arrows indicate remains of vertically set bricks. A: Room 8 ("basilica") Residential Unit 6 in Terrace House 2 at Ephesus, Turkey (mid-second century CE; see plan in Fig. 49). B: Substructure vault of the Basilica at Aspendus, Turkey. C: Detail of second-phase vault of the Baths of Vespasian at Patara, Turkey (mid-second century CE (?)). D: *Frigidarium* vault of Southwest Baths at Patara, Turkey. (Color images: WebFigs. 11–12).



35. A: Substructures of the Theater Baths at Argos, Greece (second century CE), showing vertical brick vaulting with imprints of formwork boards remaining on the intrados and the beam holes used for the centering. B: Substructures of the odeum at Thessaloniki, Greece (first half of third century CE), with beam holes located directly below vertical brick vaulting.

haunches were built up of radial bricks without centering until the point where this was no longer possible and then the upper part was filled in with pitched/vertical brick.[76] This construction method may have been possible with some vaults, but many of the Roman ones either have preserved centering holes to demonstrate the use of a wooden support structure or else the radial brick extends too far to have been built without centering. For example, at Argos in the substructures of the Theater Baths, which were later built into the sunken courtyard of the cult complex, some vaults combined radial bricks at the haunch and vertical brick vaults at the crown. These vaults clearly used centering because the imprints of the wooden formwork boards are still visible on *both* radial and vertical parts, as are the centering holes along the impost (Fig. 35A). Other examples of centering holes found together with vertical brick vaulting can be seen in the "Baths of Nero" at Olympia, in cisterns at Elaeussa Sebaste and Rhodiapolis (Fig. 19), and in the substructures of the odeum at Thessaloniki (Fig. 35B).[77]

One consideration in choosing the vertical brick for the crown could relate to the builders' perception of some structural advantage – perhaps they saw the vertical brick construction as stronger and more crack resistant. The crown of a barrel vault is commonly the first place that a crack develops, as can be seen in a vault from the Outer Baths at Hierapolis (Fig. 36). Builders observing this behavior at the crown would have naturally perceived the crown as the weak point. In fact, in most cases the cracking is a cosmetic concern; as long as the abutments do not spread substantially, the vault will remain stable. However, cracks are unnerving regardless of the inherent stability of the structure, and the builders may have wanted added insurance against them. In a radial brick vault, the mortar joints run the length of the crown and form natural lines of cleavage, whereas in a vertical (or pitched) brick vault the

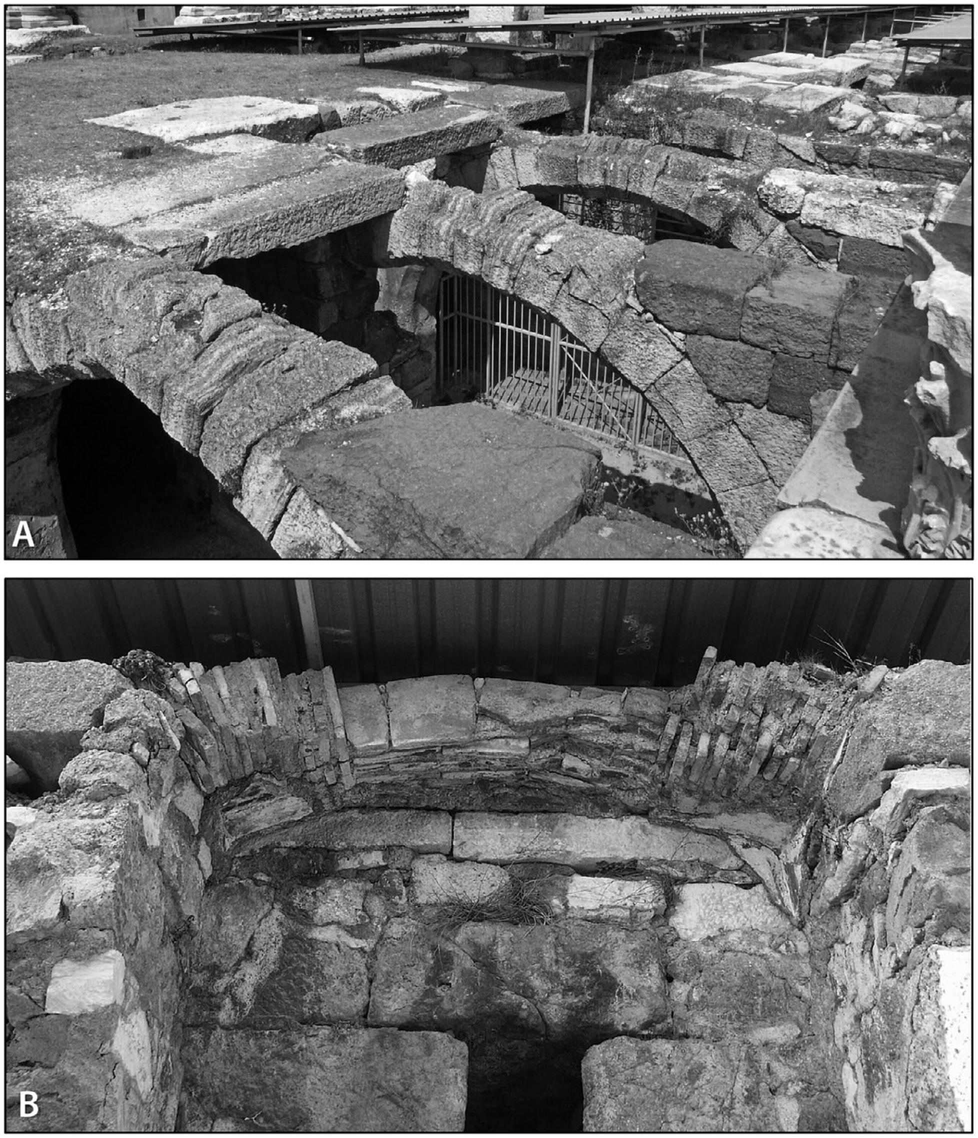


36. Outer Baths at Hierapolis, Turkey. Photo of spreading arch showing the classic hinging pattern as illustrated in diagram above.

interleaved bricks create a "zipper" effect that would have resulted in the crack having to cross through both brick and mortar, rather than forming within a mortar joint. Even a good hydraulic mortar has less tensile strength than the brick itself. For example, analysis of the bricks and the crushed terracotta mortar at the Hagia Sophia indicate that the bricks had a tensile strength of 30 kg/cm² compared to only 4–6 kg/cm² for the mortar.[78] In effect, the vertical bricks would have provided some additional resistance to tensile stresses, especially in vaults that did not use hydraulic mortar. The increased resistance to cracking of vertical (or pitched) brick barrel vaulting was already noted by Choisy when he claimed that this type of construction resulted in vaults that did not produce lateral thrusts on their abutments – although he wisely noted that relying on this theoretical state would be a grave miscalculation on the part of the builders.[79] The ancient builders, however, would not have been thinking in terms of quantifiable "tensile stresses."

The basilica in the agora at Izmir provides examples of brick vaults where the builders may have been concerned about the vulnerability of the crown. Originally the basement ceiling, which also formed the main floor level of the basilica, was constructed of flat slabs of stones supported by a series of arches (Fig. 37A, WebFig. 15), but at some point the flat stones were replaced with brick vaults that have vertical brick crowns (Fig. 37B). Because the vaults were replacing the flat slabs, they had to be very shallow. Building a flat arch of stone voussoirs is not problematic because the tight joints between the fitted stones ensure stability,[80] but building in brick is another matter because most bricks are not shaped into voussoirs, and much more stress is allotted to the mortar joints. There are no centering holes here, but centering clearly had to be used given that the radial sections at the haunches continue past the point where they should be self-supporting.[81] In this case, the use of vertical bricks was likely meant to reinforce this shallow vault at its most vulnerable point by creating a type of very wide "keystone."

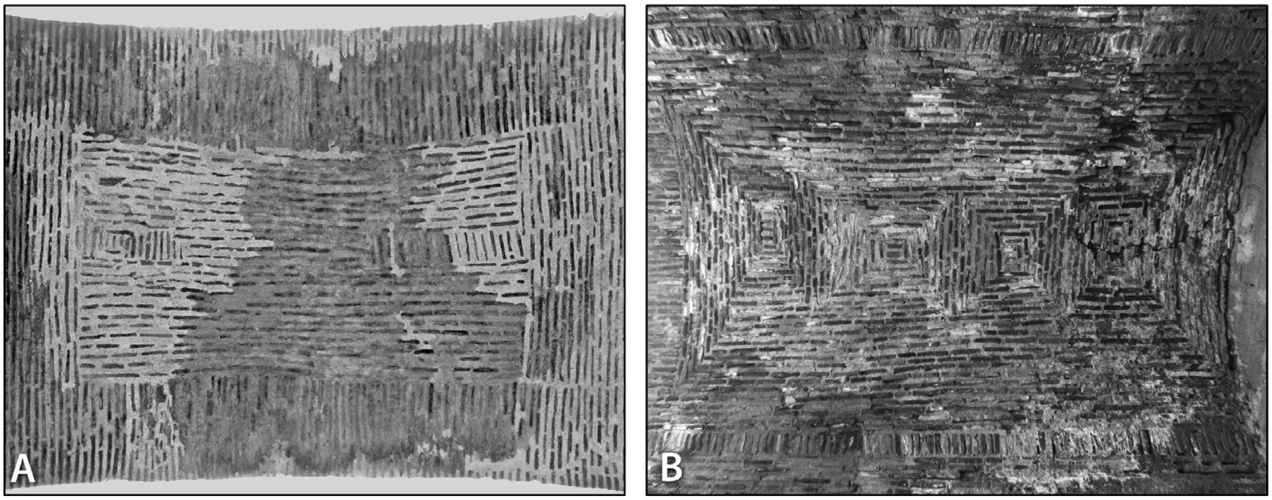
The idea of the vertical bricks at the crown being conceived as a keystone is also evident when they are set in a single row along the crown of a vault. This occurs at Ephesus in a few places: at RU6 in Terrace House 2 in a barrel vault that supports an upper level hypocaust (Fig. 38A), in shop 12 of Terrace House 1,[82] and across the street at the "Love House" (Fig. 38B). It also occurs in sections of an underground aqueduct channel at Sardis.[83] The same idea was used at the crown of the two semidomes in the central bays forming the *nymphaeum* at the basilica at



37. Substructure vaults of the basilica in the agora at Izmir, Turkey. A: Original stone paving slabs supported by arches (second century CE). B: A section where the paving slabs were replaced by shallow brick arches made up of radial and vertical bricks. Note that the radial brick extends far enough from the wall to have required centering.

Sparta.[84] This technique of setting vertical bricks as a type of keystone spine was presumably a variation on the practice of employing more solid materials at the crown of a vault, such as the three-stone spine at the Small Baths at Aspendus (Fig. 38C) or the radial brick spine in the mortared rubble vault of the cryptoporticus at the forum complex at Coimbra in Portugal (Fig. 38D).[85] In all cases, the use of a spine along the crown seems to have been a means of providing a type of reinforced keystone. In this regard, an informative example can be seen in a cistern below the paving of the agora at Cremna in Pisidia, where the crown of the mortared rubble vault is reinforced with cut stone voussoirs (WebFig. 16).[86]

38. Examples of keystone spines of different materials at the crown of barrel vaults. A: Residential Unit 6 in Terrace 2 at Ephesus (second century CE) with spine of vertical bricks in otherwise radial brick vault. Note the hypocaust above the vault. B: "Love House" at Ephesus with spine of vertical bricks. C: Small Baths at Aspendus (second century CE). Brick barrel vault with a spine of three stone voussoirs. D: Cryptoporticus at the forum at Coimbra, Portugal. *Opus caementicium* vault with spine of radial bricks (photo: Miriam Shadis).



39. Barrel vaults with sections of vertical brick. A: Arch of Galerius at Thessaloniki (early fourth century CE). B: Room from outer precinct enclosure of St. John's at Ephesus (sixth century CE).

Finally, a different use of vertical bricks appears in some late antique barrel vaults where the bricks are set vertically in rectangular sections at the crown of the vault. This technique can be seen in the barrel-vaulted niches of the Rotunda of Galerius in Thessaloniki and also in the remaining bay of the nearby Arch of Galerius (Fig. 39A).[87] An example has recently been found in a vault under the Scholastica Baths at Ephesus.[88] This technique became more common in the Byzantine period and is visible in barrel vaults elsewhere at Ephesus at the churches of St. Mary and St. John (Fig. 39B).

TECHNOLOGY TRANSFER AND THE NEAR EAST

The question arises as to why this new technique of using vertical bricks suddenly appeared in Greece and Asia Minor during the first half of the second century CE. That it came from the Near East or Egypt was proposed by Ward-Perkins as early as 1958,[89] but can its origins and the agency by which it came westward be further refined? If so, then we can begin to put the constructional innovations into a broader sociopolitical context. We have seen that the Roman builders working in the Fayum in Egypt were building pitched mud brick barrel vaults in their utilitarian and residential architecture. Indeed, P. Aupert, the excavator of the cult complex at Argos, argued that it was originally dedicated to the Egyptian god Serapis before it was later associated with Asclepius and that the vaulting technique of setting the bricks vertically ("*par tranches*") came from Egypt, possibly with the workers or architect who built the structure.[90] However, a close examination of the details of the earliest Roman examples in Greece points to Parthia as a more likely source of inspiration.

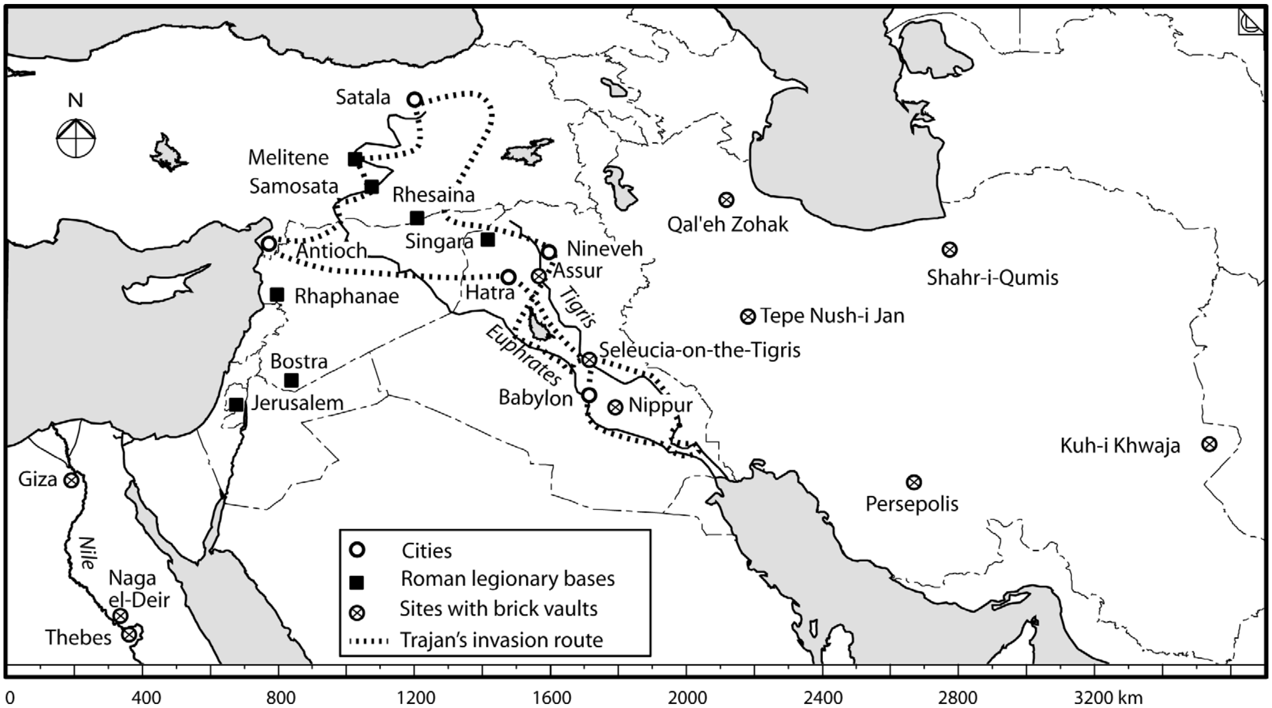
The construction details that characterize the earliest Roman examples include (1) the setting of the bricks vertically rather than pitched (Athens, Eleusis, Argos, Ephesus), (2) the use of the preformed curving bricks to create the three-brick arches (Athens, Eleusis), and (3) the combined use of radial bricks at the haunches and vertical bricks at the crown of barrel vaults (Argos, Ephesus). Each of these characteristics has precedents in Parthian architecture during the centuries just before their adoption in Roman architecture, whereas precedents in Egyptian architecture are rare and typically date many centuries earlier.

The first characteristic, vertically laid brick, occurs in large-scale vaults of fired brick in the Parthian architecture of the first century CE at a time when there was direct contact with the Romans. It also occurs in Egypt, but the examples there are of mud brick and are much earlier, ranging from the third to the first millennium BCE.[91] The most advanced examples thus far excavated covered a hall in the royal Parthian palace at Assur (first century CE). The vaults no longer remain standing, but the excavators in the 1930s found enough of the fallen pieces of arches and vaults so that a reconstruction was possible.[92] A series of three parallel barrel vaults (3.5 m span) were supported by mud brick pillars connected by fired brick arches of vertically laid brick, the largest of which was five meters wide (Fig. 25).[93] Apparently the practice of placing the bricks vertically developed from the need to build arches within the vertical faces of walls once Parthian palace architecture became more complex. Roman architects and engineers accompanying Trajan during his war in Parthia (114–116 CE) would have been exposed to this new mode of building.

The second characteristic is the use of the three-brick arch construction. This appears to be derived from the use of long prefabricated mud brick struts, which appear at the Median site of Tepe Nush-i Jan in Iran (eighth–sixth century BCE) (Fig. 25) and later in the Achaemenid fortifications at Persepolis (sixth century BCE).[94] This technique was also used in the seventh-century BCE structure at Tell Jemmeh (Fig. 25) in Israel where the doorways of a vaulted substructure were built with struts like those at Tepe Nush-i Jan. The excavator of Tell Jemmeh, G. Van Beek, suggested that this Assyrian outpost on the Mediterranean was designed by a Median architect brought from farther east.[95] The idea of the curved strut reappears in a shortened form in an early example of a three-brick arch (2.30 m span) in the Parthian funerary structure on Site VII at Shahr-i-Qumis in northern Iran (first half of the first century BCE) (Fig. 25).[96] The technique continued to be used for four centuries, as can be seen in the third-century CE (?) palace at Kuh-i Khwaja in southeast Iran where examples of both three-brick and five-brick arches exist.[97] In Egypt, preformed curved trapezoidal bricks were used in the New Kingdom tombs at Dier el Medina, such as the Tomb of Sennedjem, and three-brick arches of straight rectangular bricks occur over small openings (Fig. 25), but the two ideas apparently did not come together in the same type of modular unit as found in the Parthian examples.

The third defining technique employed in the Roman vaults is the combined use of radial bricks at the haunch and vertical bricks at the crown. This hybrid technique has its origins in Parthia and to my knowledge does not occur in Egyptian vaults. The combining of radial and *pitched* mud bricks can be seen in a tomb at Seleucia-on-the-Tigris (3.2 m span; mid-first to early second century CE) and at Nippur (Fig. 25).[98] The most direct parallel, however, occurs in the first/second-century CE quadrifrons arch at Qal'eh Zohak,[99] the central arch of which has radial bricks at the haunch and vertical bricks at the crown (Fig. 25). As at the pillared hall in Assur, the bricks could not be pitched because they formed the vertical face of a wall.

Taken together these three constructional characteristics of Roman vertical brick barrel vaults suggest that the initial inspiration likely came directly from Parthia rather than from Egypt. The fact that they appear in Hadrianic structures just after Trajan's Parthian War points to military architects and engineers as likely agents (Fig. 40). Indeed, the technique was found in a Severan military outpost at Ain Sinu in northern Iraq. The bricks of a barrel vault covering a roadway in the camp were set vertically rather than pitched, which caused the excavators (more familiar with eastern practices) to note that "the [Roman] builders apparently did not understand the principle



40. Map showing locations of pre-Roman brick vaults (mostly mud brick) mentioned in Chapters 3 and 4, along with the course of Trajan's invasion route during the Parthian War.

of this method, whereby each successive ring of bricks is set at an angle, supported by its predecessor."[100] Lack of understanding on the part of the Roman builders is an unlikely explanation; instead, the use of the vertical brick technique in a Roman military context in a region known for pitched brick is another reason to believe that its initial introduction farther west was due to military oversight. At Dura-Europus, home to a Roman garrison, the Severan bath M7 has a vaulted room in the substructure with a crown of either pitched or vertical fired bricks (orientation not specified), which may also represent a confluence of Parthian and Roman military expertise.[101]

CONCLUSIONS

Now I return to the questions posed at the beginning of the chapter: where, when, and why? Sporadic examples of brick vaulting occur in Italy before the imperial period, often in underground tomb structures, and P. Vitti has recently shown that it was being used in above-ground structures in Greece by the early first century CE. The introduction of brick vaulting in Asia Minor appears somewhat later and at a larger scale. By the late first century CE, the cities in the province of Asia, especially Ephesus, had risen to prominence, as had the political power of the native elite, with some even making their way into the Roman senate. In the major cities, there had been significant building programs employing cut stone and mortared rubble since the Augustan period, but during the second century brick began to be adopted on a larger scale, first in the solid walls of the Library of Celsus and then elsewhere in vaults, especially of bath buildings. Why suddenly in the late Trajanic period did brick begin to be used in ways it had not been earlier? As U. Wulf-Rheidt has pointed out, the ubiquitous use of brick in Rome was due to the centralization of the brick-producing industry that supplied imperial projects and that eventually was entirely controlled by the emperor himself. Production in the provinces could never achieve the same economy of scale. Moreover, in Asia Minor the long tradition of stonework created supply lines at quarries and skilled workers who had cultural and possibly even political leverage.[102] A sudden reliance on brick as in Rome would have upset established economic patterns. Nevertheless, the new material did make inroads into the building tradition, at least along the coasts and rivers where clay was readily available.

The initial impulse toward the use of brick is often credited to Ti. Julius Celsus Polemaeanus (*cos* 92 CE), whose remains were entombed in his library at Ephesus and who had been in Rome both as consul and as *curator aedium sacrarum et operum locorumque publicorum* before returning to Asia as proconsul in 105/6 CE.[103] The library was built by his son, Ti. Julius Aquila Polemaeanus (*cos* 110 CE) around 114–117 CE. V. M. Strocka, in his study of the Library of Celsus, suggested that the use of brick could be attributed to the family's direct connection with Rome, with both father and son having served in the senate. He suggested that the use of bricks was inspired by the brick construction in Rome and that the bricks could have even been produced on the local properties of this wealthy family.[104] M. Waelkens picks up on this idea and suggests that imitating the brick construction of the capital was a way for Celsus and Aquila to express the family's "*Romanitas*."[105] The idea that the bricks for Celsus's library were produced on the family's landholdings is an intriguing one, as is the clear connection with Rome.

The use of brick may well have been inspired by its ubiquitous use in Rome; however, rather than seeing the adoption of brick in Asia Minor simply as a desire to imitate the *construction methods* in Rome, an alternative explanation may be that the landowners in these areas were imitating a new mode of *property exploitation* that had become common around Rome. H. Bloch linked the threefold rise in the number of brick *figlinae* (brick yards) around Rome during the first decade of the second century to a law mentioned by Pliny the Younger in which Trajan compelled provincial candidates for public office to invest a third of their capital in property in Italy.[106] This was precisely the period during which Aquila was consul. Indeed, in the subsequent generations we find a stamp from Rome with the name Ti. Claudius Julianus, the grandson of Celsus, who according to an inscription on the library donated two of the bronze statues set up there.[107]

Other evidence from Rome suggests that the landowning elite from the Greek East were involved in the brick-making industry in the capital. A few of the stamps from Rome list landowners who have been identified as members of the provincial elite from Asia Minor: Cusinius Messalinus and his daughter Cusinia Gratilla from Ephesus and possibly Ti. Claudius Celsus Orestianus from Pergamum.[108] One stamp (153 CE) has been linked with L. Cuspius Pactumeius Rufinus (*cos* 142 CE),[109] who was a friend of Celsus's grandson, Ti. Claudius Julianus,[110] and who sponsored the Temple of Asclepius at Pergamum (which had the brick dome). This structure was begun some time during the Hadrianic period and was a clear imitation of the Pantheon, which was completed around 128 CE.[111] His identification on the stamp is not absolutely certain because the full nomenclature is not given, but here we may have a senator from Asia Minor who owned brick-producing properties in the Tiber valley and who sponsored one of the early brick vaulted structures in his homeland. The brick stamp evidence from Asia Minor is not well documented, and the known stamps are more laconic than those in Rome – most have only a single name in Greek. We know, however, that owners (often absentee) of large private estates in Asia Minor regularly leased their lands to freeborn indigenous people or to their own freedmen to work, as demonstrated by inscriptions from the area around Cybyra in Phrygia.[112] Thus the use of bricks in the walls and vaults of buildings could certainly have been an expression of *Romanitas*, as has been noted for the use of *opus reticulatum*,[113] but at the same time, their production could also have been a lucrative means of exploiting local landholdings containing clay beds and fuel sources.

With regard to how the bricks were produced and who benefited economically, other types of landowners could also use properties for brick and tile making, including cities and sanctuaries, both of which had accumulated vast tracts of land during the Hellenistic period.[114] For example, H. Thür has recently noted a stamp from Terrace House 2 in Ephesus with the Greek letters APT and a bee insignia, which clearly refers to the city's patron goddess Artemis who is associated with the bee (which also appears on coins of Ephesus).[115] It is an intriguing hint that the sanctuary itself was involved in brick production during the second century when the main phases of the Terrace Houses were remodeled. The Sanctuary of Artemis is known to have had significant landholdings in the Cayster valley around Ephesus and to have rented them out.[116] Because it is unlikely that the sanctuary was directly involved in remodeling the private homes in the Terrace Houses, the stamp could represent simply that the brick was made on sanctuary property as one of a variety of ways of extracting income from its landholdings.[117]

Evidence for municipal production occurs on a brick (from an undated context) at Sagalassos, which was stamped with ΠΟΛ(έοσ), or *poleos* (of the city).[118] Such municipal stamps are found throughout the empire in both the East and West, usually (but not always) on roof tiles. A particularly informative type appears on roof tiles from the odeum at Corinth (second half of the first century CE). They have the abbreviation for the colony's name (COL(*onia*) L(*aus*) IVL(*ia*) COR(*inthus*) or Κ(ολονεια) ΛΑΩ(σ) Ι(ουλια)) plus initials or an abbreviated form of the brick maker's name. The colony stamp and the maker's stamp were usually separate dies.[119] If the colony was contracting with different makers to use its land for making bricks, the two stamps could represent each party in the contract. Likewise, some quarry inscriptions and graffiti suggest similar arrangements may have existed for municipally owned quarries.[120] A contract preserved on a third-century CE papyrus from Oxyrhynchus in Egypt details the arrangements made between potter and landowner, whereby the landowner provides the workshop with its equipment along with the clay and fuel for firing, while the potter provides the laborers and the end product, which will belong to the landowner.[121] In such an arrangement for bricks, the landowner could either sell the bricks or use them for a project he was funding. The profit-making potential of brick making is only one of many factors that could have affected the initial popularity of brick vaulting in the East. Without further evidence it is difficult to know the precise nature of the legal structure within which the landowners (private, municipal, or sanctuary) and the brick makers in Asia Minor were working. The important point, however, is to distinguish between the idea of simply imitating the brick construction in Rome as a means of expressing identity and that of imitating property exploitation as a means of turning a profit. Thus, the increasing popularity of bricks in construction during the second century could be seen as a type of innovation affected by *social acceptance*.

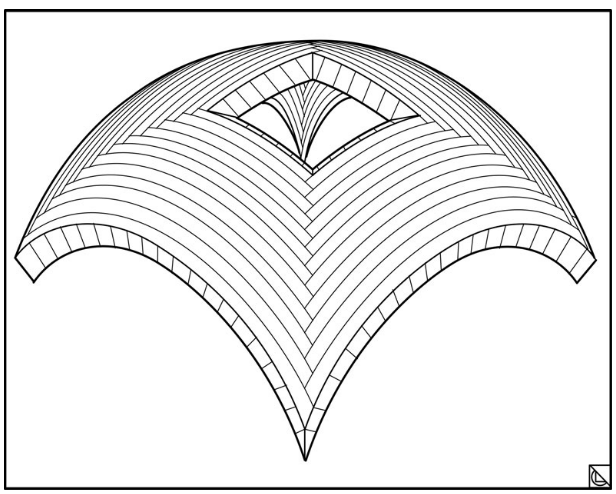
The introduction of vertical brick vaulting introduces yet another thread in the web of factors that affected technology transfer in the eastern empire. The adoption of radial brick vaulting largely involved a change in material; the units themselves were still conceived as voussoirs so that brick was imitating stone. Vertical brick vaulting, in contrast, represented a conceptual change in how and why the material was used. I argue that vertical brick vaulting appeared first in Greece during the Hadrianic period and that it was used initially for fairly specialized situations in small vaults, such as aqueduct and drainage channels. Given the unique characteristics of these earliest examples, such as preformed curved units and vertical bricks at the crown in combination with radial at the haunches, I suggest that the idea was appropriated from Parthia, which is the area that provides the closest parallels. The most likely agent for the introduction of the new technique would have been military personnel just returned from Trajan's Parthian War (Fig. 40). The fact that these early examples relate to urban aqueduct and drainage infrastructure puts them in a special category where the military is known to have had expertise. The extraordinary vaulted structure at the Argos cult building with its singular double-shelled roofing scheme is in a different category; nevertheless it was linked to the construction of the south aqueduct, which supplied a fountain in the first phase of the cult complex.[122] In this sense it too could be seen in the context of an overall Hadrianic building program that focused on two of his major initiatives: the reinvigoration of the cult practices in Old Greece along with the investment in infrastructure, which in this case involved specialists working on the water supply and drainage system.[123]

Regarding the introduction of vertical brick construction into Roman architecture, one may reasonably ask, "If the Romans were in conflict with Parthians from the mid-first century BCE, why would such technical knowledge only come westward in the second century CE?" The answer is probably twofold. First, as discussed earlier, the early second century was a boom time in Rome for brick production, and the brick stamps allow us to see how brick production provided economic potential for both landowners and brick makers. Thus bricks as a building material suddenly had an enhanced appeal. Second, the new technique seems to have been first adopted in Greece where brick vaulting had already become accepted practice. The new technique was also introduced during a wave of bath building, which required various other types of terracotta elements. The new curved and trapezoidal bricks were happily adopted as part of the bath building "kit." The introduction of vertical brick vaulting is a classic example of how innovations happen. The *invention*, in this case pitched mud brick, can occur far away in both time and place, whereas the *innovation* only happens when various factors within society (know-how, need, economics, and open minds) come together at a specific time and place. Once it catches on, then *diffusion* occurs.

4

COMPLEX VAULT FORMS OF BRICK

Pitched brick construction lent itself to the creation of a number of vault forms that are more complex than the simple barrel vault. In the previous chapter I distinguished between barrel vaults employing pitched bricks as opposed to vertical bricks, but the same distinction does not apply for other forms. Pitched brick was particularly useful for vaults with four or more springing points because the pitched arches along each side could be built up simultaneously to form square "rings" (Fig. 41), which held each other together once in place and eliminated the need for wooden centering. As with barrel vaults, the roots of the technique originate in much earlier architecture in the Near East and central Asia, but the forms in which they were used in Roman architecture have a more diverse developmental history than the barrel vault.



41. Drawing of pitched brick sail vault before the completion of the crown.

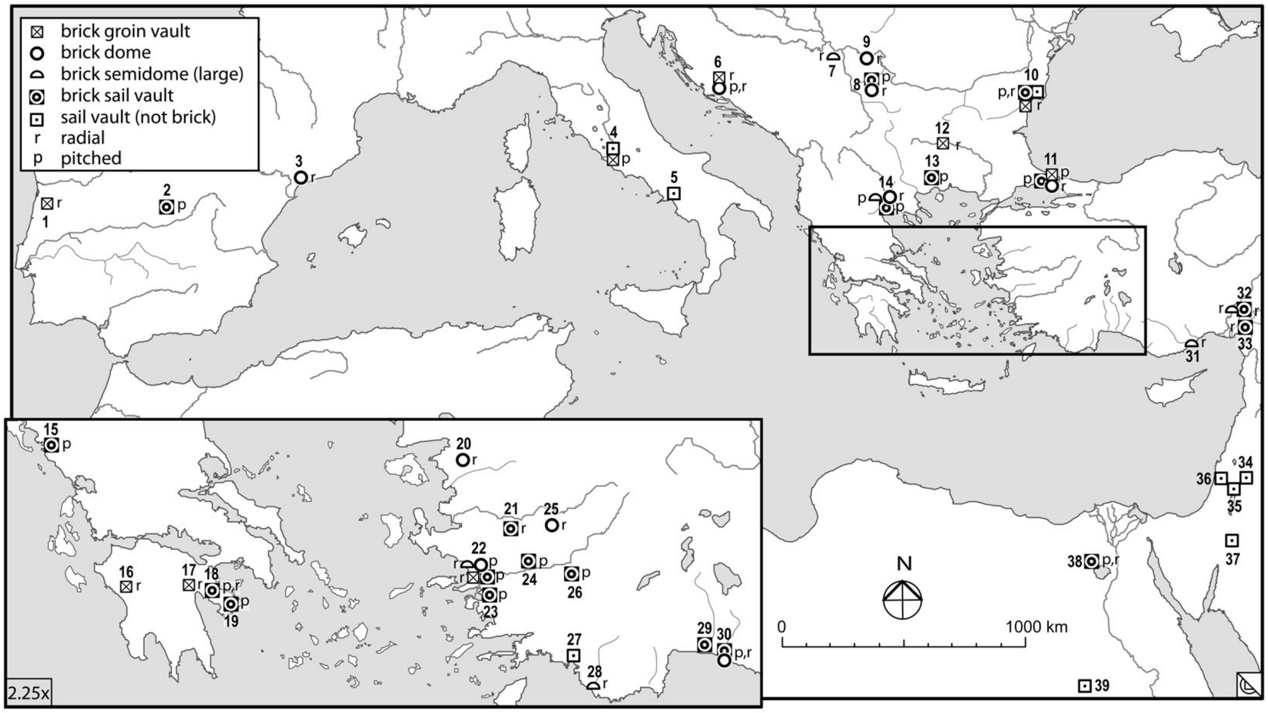
As with vertical brick vaults, the use of pitched brick was almost exclusively confined to the eastern empire (Fig. 42, WebCat. 4-B).[1] The technique could be used to build a variety of different forms, but the one that occurs most often is the sail vault. This was a new vault form that appeared in Roman architecture in the East, so I look at the development of both the form itself and the pitched brick technique that was often used to build it.

Questions addressed in this chapter include the following: What advantages (constructional or structural) did pitched brick offer for various vault forms? Did the technique define the form or was it adapted to preexisting forms? What role did theoretical advances in geometry have on the development of vault forms and the way in which they were built? What are the cultural influences behind the adoption of pitched brick for the sail vault?

VAULT TYPES: TERMINOLOGY

One of the earliest of the complex pitched brick forms is what O. Ruether called a *squinch vault*

Catalogs (WebCat.) and color figures (WebFig.) can be downloaded at www.cambridge.org/vaulting

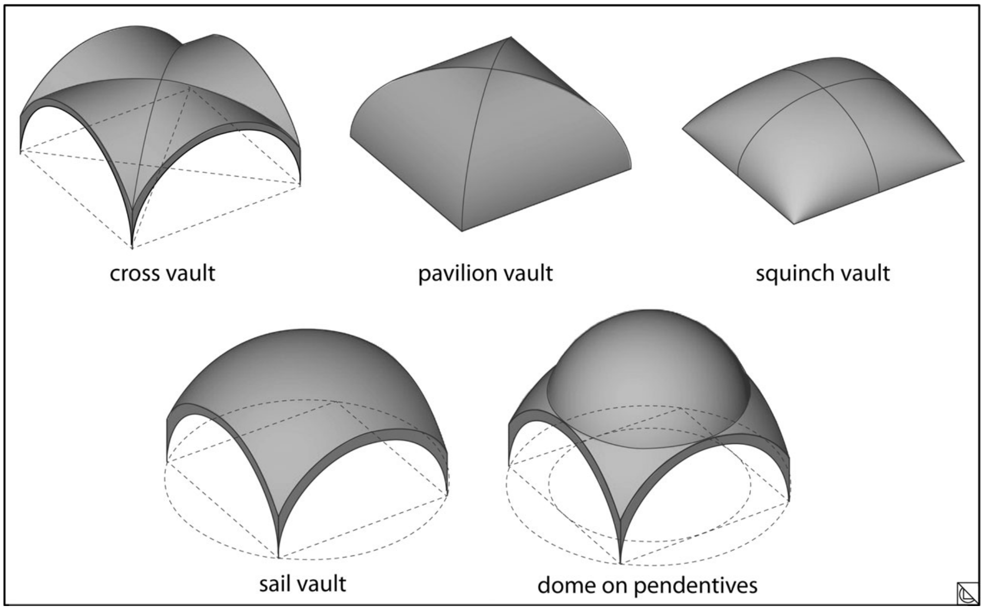


1 Coimbra, **2** Carranque, **3** Centcelles, **4** Rome, **5** Minori, **6** Split, **7** Brestovik, **8** Gamzigrad, **9** Sarkamen, **10** Varna, **11** Istanbul, **12** Plovdiv, **13** Philippi, **14** Thessaloniki, **15** Riza, **16** Olympia, **17** Argos, **18** Epidaurus, **19** Troezen, **20** Pergamum, **21** Sardis, **22** Ephesus, **23** Magnesia on the Meander, **24** Nysa, **25** Philadelphia, **26** Aphrodisias, **27** Lydai, **28** Patara, **29** Aspendus, **30** Side, **31** Corycos, **32** Anazarbus, **33** Küçük Bernaz, **34** Qusayer an-Nuwayis, **35** Sebastya, **36** Jerash, **37** Petra, **38** Fayum, **39** Ezbet Bashendi

42. Distribution map of pitched brick vaults of double curvature (domes, semidomes, sail vaults) and of nonbrick sail vaults made of mortared rubble or cut stone (WebCat. 4).

(the German *Trompengewölbe* [trumpet vault]).[2] It was made by building up successive pitched arches across each of the four corners of a room until they met in the center as four cone-like segments (i.e., the squinches) (Fig. 43). The gap remaining in the center could be filled either by continuing the arches so that they met along the centerlines of the room or by changing the direction of the arches to span between the angles of the opening. The resulting vault sprang from all four walls of a square or rectangular space without any intersecting groins. A similar form in Graeco-Roman architecture, albeit with groins, is the pavilion vault (or cloister vault), such as those of *opus caementicium* in the Tabularium at Rome (78 BCE). It is made up of four half barrel vaults intersecting along the diagonals (Fig. 43). This form is defined by intersecting arcs, the geometrical shape of which facilitates the construction of the wooden centering used to build it.

The cross vault developed much later than the squinch vault and is different in that it springs from the four corners, rather than from the walls (Fig. 43). It was originally devised for cut stone construction, an early example of which occurred at Delphi in a structure dedicated by Attalos I (second half of the third century BCE).[3] When it was translated into brick construction, the bricks could be laid either radially (most common) or pitched. For a pitched brick cross vault, the builder began by building arches parallel to the four walls; however, the pitched brick cross vault was rare before the sixth century CE (WebCat. 4-A,B).[4]



43. Complex vault forms discussed in Chapter 4.

The most common form built with pitched brick is the sail vault (the Italian *volta a vela* and the German *Hangcüppel*). In English scholarship, it has also been called a *pendentive dome* or a *dome with continuous pendentives*. This terminology has led to great confusion regarding the sail vault's relationship to the Byzantine-type dome used at Hagia Sophia, which is a *dome on pendentives* (Fig. 43). To avoid such confusion and to make a clear distinction between the two types of vaults, I use the term *sail vault* in place of the more ambiguous terms, *pendentive dome* and *dome with continuous pendentives* (despite the fact that sail vaults do have pendentives as an inherent part of their geometry). The pendentive is the concave triangle that fills the angle between two walls and provides the transition to the circle defining the base of the dome. In a sail vault, the pendentives are defined by the same sphere defining the dome, whereas in a dome on pendentives, they are defined by a larger sphere than that defining the dome (compare in Fig. 43). The two configurations are quite different in geometry and should not be conflated because the sail vault developed much earlier than the dome on pendentives. In the period under examination (first to early fourth centuries CE) we are dealing exclusively with sail vaults.

COMPLEX VAULT FORMS: PRE-ROMAN DEVELOPMENTS

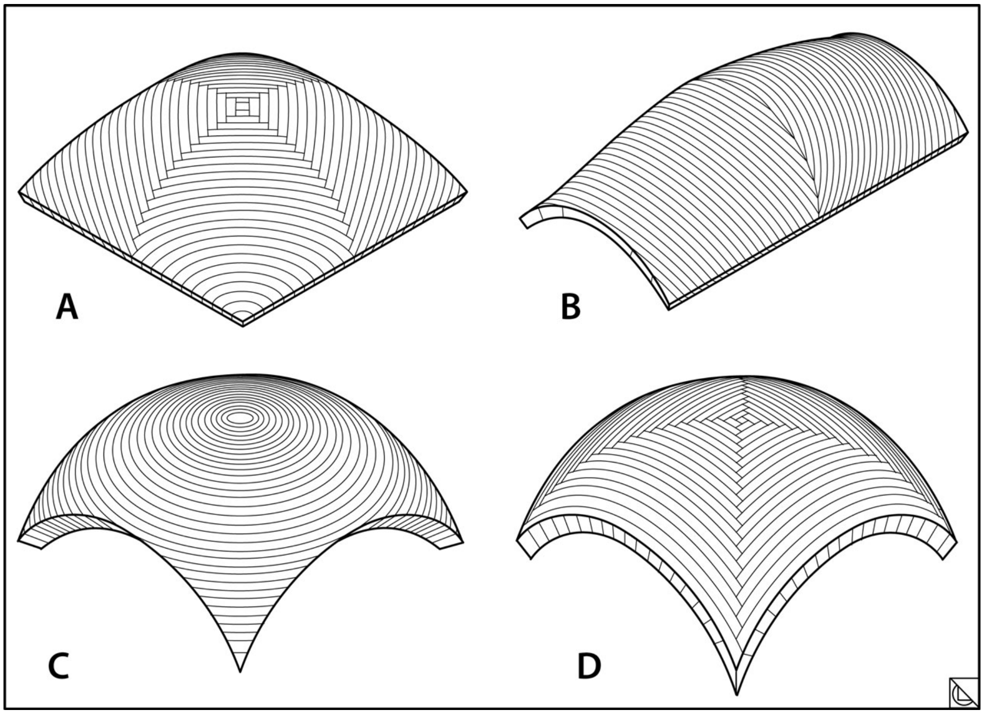
The squinch vault is the earliest of the complex vault forms to employ pitched brick. Examples that date to c. 2000 BCE occur at Tell al Rimah in Iraq.[5] The resulting form (2.30 × 1.40 m) was very shallow with a rise of only 25 cm. The shape of the vault was determined by the construction process rather than by any geometric principle. The arches spanned the corners until they met in the middle of the long wall; then the resulting opening was filled with pitched arches and the hole in the middle plugged with brick fragments. A much more developed form of the squinch vault (c. 9 m span) occurs at the Graeco-Bactrian site of Delbarjīn, Afghanistan, at a well house attached to a wealthy residence/palace (c. 100 BCE). Only the springings at the corners have survived to show that the central room over the wellhead was covered, but parts of the pitched mud brick barrel-vaulted corridors surrounding it indicate a sophisticated understanding of the necessity for buttressing such a large vault.[6] Delbarjīn is located far from the Mediterranean, but it nevertheless had become hellenized after Alexander's eastern campaigns and exhibits a mix of classical decorative motifs and indigenous building methods, as well as extensive use of the Greek language.[7] Structures such as this well house give some idea of the types of developments that were occurring in mud brick that have not survived as well as the later fired brick vaults of the Roman world.

The squinch vault was transformed during the Sasanian period (224–650 CE) to act as a transitional element to support circular domes placed above square rooms.[8] In this sense its function was comparable to that of the pendentives that supported Byzantine domes. The use of squinches to act as transitional elements for a dome set on a square base continued to be employed in Sasanian architecture even after the pendentive was adopted in Roman and Byzantine architecture, and it became of a hallmark of early Islamic architecture.[9]

The invention of the sail vault has often been pinpointed to second-century CE Syria,[10] but in fact it goes back to the Early Dynastic period in Mesopotamia and to pharaonic times in Egypt. In the Royal Cemetery at Ur in Iraq, L. Woolley excavated a tomb (PG/1054) covered by a crude sail vault (2.5 m square) made with corbeled unhewn stones.[11] Other tombs in the cemetery had a similar type of construction for small domes or apses in both unhewn stone and fired brick. In all cases, the pendentives making the transition from square to circle were corbeled, and the dome was built with sloping courses, though not true radial courses. The date of the tomb is debated, but can be placed some time between the mid-fourth and mid-third millennium BCE. Similarly, in Egypt the earliest sail vault can be traced back to the mid-third millennium at Giza in the Fourth Dynasty mastaba tomb of Seneb, a dwarf who served as a high-ranking palace official.[12] The mud brick sail vault covered a small square room (2.0 × 2.0 m) with stone walls, and the pendentives were formed by corbeling. A later, anonymous Middle Kingdom tomb (c. fifteenth century BCE) at the Dra' Abu el-Naga' cemetery on the west bank at Thebes was also covered by a mud brick sail vault (2.2 × 2.4 m).[13] The pendentives sprang from a brick placed diagonally across the corner and then rose in corbeled layers. On its discovery in 1906, the upper part of the dome was no longer preserved well enough to determine how the upper bricks were placed. These very early examples demonstrate that the idea of a sail vault, which transitions from a square to a circular base, originally developed in both Mesopotamia and Egypt using corbeling. It was not adapted to pitched brick construction until the Roman period.

MUD BRICK SAIL VAULTS IN EARLY ROMAN EGYPT

To trace the entry of the sail vault into Roman architecture and the development of the pitched brick technique to build it, we must turn to the remains of Roman settlements in the Fayum in Egypt. The sites of Karanis (modern Kom Aushim) and Soknopaiou Nesos (modern Dime) were excavated by the University of Michigan between 1925 and 1935. The structures at both sites are now largely reburied under the dunes and no longer visible, so the main evidence consists of the site drawings and photographs from the excavations. The results of E. E. Petersen, director of the Karanis excavation, were summarized and published almost a half-century later by E. M. Husselman in 1979. The work at Soknopaiou Nesos, which only

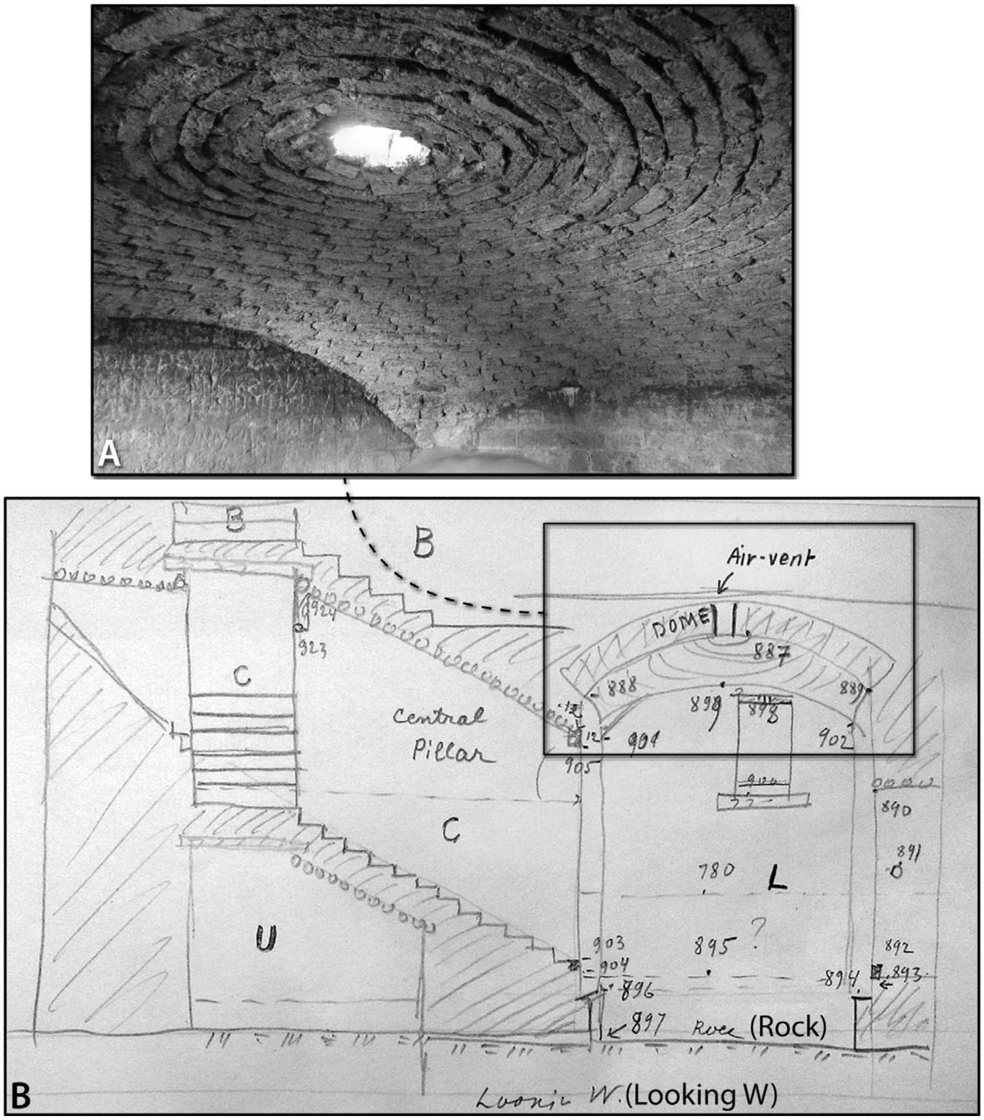


44. Mud brick vault types found in the Fayum, Egypt, during the Roman period. A: Squinch vault. B: Arched barrel vault. C: Radial brick sail vault. D: Pitched brick sail vault (laid parallel to walls).

lasted one season and included two separate blocks of houses, was published by A. E. R. Boak in 1935. Both publications are summaries of the major results, and much material remains unpublished in the archive at the Kelsey Museum at the University of Michigan; therefore, the true relevance of these sites for the history of vault development has not been fully appreciated.

A search through the Karanis archives revealed thirty-four examples of vaults that were often labeled as "domes" on the site sketches to distinguish them from the more typical barrel vault. These vaults actually comprise three different forms: the sail vault, the squinch vault, and an unusual vault form that I call an "arched barrel vault" (Fig. 44). Because the earliest pitched brick sail vault outside of Roman Egypt does not appear until the second century CE, those in the Fayum provide valuable information on the early development of both the form and the pitched brick technique of building it.

The earliest known sail vault (3.5 × 4.1 m) from the Fayum occurs in an unusual structure at Soknopaiou Nesos (house II.201). Though the structure is called a "house," Boak notes that it "differed strikingly from all other houses excavated at Soknopaiou Nesos or at Karanis" and suggested that it was some other type of public building.[14] It was built more substantially and decorated more elaborately than the typical houses at either site, with a single entry that led into a vestibule covered with carefully crafted wooden wainscoting. The vestibule gave access to a stair that led up to the main floor and down to the underground rooms, which Boak notes "had barrel-vaulted ceilings, made of the large flat bricks, 32 × 25 × 6 centimeters, customarily employed in basement vaults."[15] However, he never mentions that the room directly under



45. A: Photo of sail vault covering room L of house II.201 at Soknopaiou Nesos (photo: Stefano Camporeale). B: Site sketch of section through room L in house II.201 (Kelsey Museum of Archaeology, University of Michigan).

the entry vestibule was covered by a sail vault built of radially laid mud bricks, which is clearly indicated in one of the unpublished excavation sketches and is still accessible on the site (Fig. 45). The building was constructed directly onto the bedrock and therefore belongs to the earliest phase in this area of the site, which has been dated to "the opening years of the Principate" based on coins found in the area. Of the five coins in this house, two are Ptolemaic, two Augustan (2–14 CE), and one Neronian,[16] but none came from sealed deposits.

Karanis provides a greater range of vaults than does Soknopaiou Nesos. Most of the vaults covered the underground cellars of houses. Of the 108 houses

TABLE 2. *Complex vault forms at Karanis*

House	Vault form	Brick pattern	Ground level	Dates (CE)
C84H	sail	pitched parallel	bedrock?	early 2nd c.?
C151	sail	pitched parallel	–	
C28F	sail	radial	–	
C37J	sail	radial	–	
C37K	sail	radial	–	
C42F	sail	radial	bedrock	mid 1st–early 2nd c.
C43G	sail	radial	bedrock	mid 1st–early 2nd c.
C51H	sail	radial	bedrock	mid 1st–early 2nd c.
C62J	sail	radial	bedrock	mid 1st–early 2nd c.
C191F	sail	radial	–	
C53	squinch	pitched diagonal	–	
C67H	squinch	pitched diagonal	bedrock	
C91B	squinch	pitched diagonal	bedrock	early 2nd c.
C194F	squinch	pitched diagonal	–	
C418H	squinch	pitched diagonal	–	
C67B	arched barrel	pitched	bedrock	
C67F	arched barrel	pitched	bedrock	

examined at Karanis, only 15 houses had vault types other than barrel vaults. Of a total of seventeen non-barrel vaults (Table 2), there were two arched barrel vaults, five squinch vaults (Fig. 44A), and ten sail vaults, eight of which were built with radial construction (Fig. 44C). Four of the radial sail vaults (C42F, C43G, C51H, C62J) were built directly onto the bedrock and can be dated to the earliest part of Phase C (mid-first century CE to the first half of the second century).[17] Also found in the same neighborhood are three houses with pitched mud brick squinch vaults (C53, C67H, C91B), of which two are built directly on bedrock. Two other sail vaults (C84H, C151) were built with pitched brick laid parallel to the walls (Fig. 44D). Husselman does not deal directly with the dating of these houses, but Peterson, in his unpublished manuscript, notes that houses C84, C85, C113, and C91 are all interrelated, and he dates the pigeon tower of C91B, which has one of the squinch vaults, to the early second century CE.[18] If these four houses are indeed contemporary, the builders appear to have continued to use the "old-fashioned" squinch vault in C91 while experimenting with the newly developed pitched sail vault in C84. Most of these rooms with squinch or sail vaults are slightly rectangular with wall length ratios between 1:1.15 and 1:1.23. Only a couple (C43G, C48H) come close to being square, so the choice to use a squinch vault as opposed to a sail vault does not seem to be related to the form of the room. Longer rectangular rooms, however, employed barrel vaults or arched barrel vaults. We have no evidence to determine whether the radially laid sail vaults were built with centering or not, but given that the other mud brick vaults throughout the Fayum were built without centering, it seems likely that the builders here were exploiting the double curvature of the dome and its unique properties (Chapter 1) to build these vaults without centering.

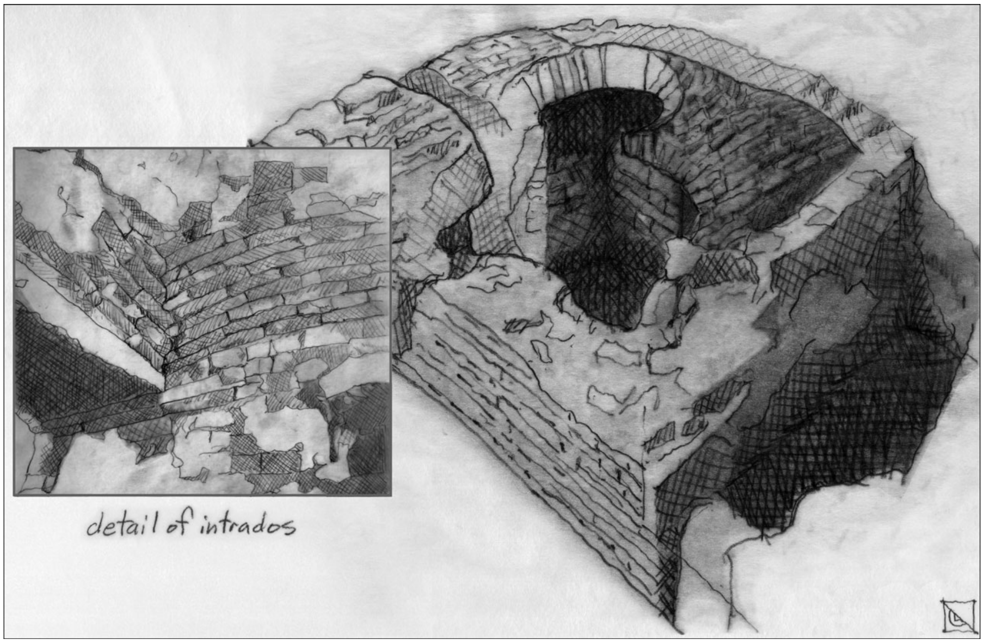
A third vault form, the arched barrel vault, occurs at both Soknopaiou Nesos and Karanis. It springs from two flat imposts with pitched brick arches at either end that lean in opposite directions so that they meet in the center (Figs. 44B & 46). This type never occurs in Roman architecture outside of Egypt, but it appears to have had a long history, given that

46. Photo of an arched barrel vault in room M of house I.108 at Soknopaiou Nesos (KM 5.3922, Kelsey Museum of Archaeology, University of Michigan).

L. Woolley described a similar form at Ur from the fourth/third millennium BCE. His explanation for the "hump" in the vault is that the pitched brick rings started at either end and each successive ring was made slightly higher than the previous one to take advantage of the greatest amount of contact surface, so the vault became progressively higher toward the center.[19] Indeed this is the earliest of the three forms found in the Fayum. It occurs in house I.103 at Soknopaiou Nesos, which is dated to the pre-Roman period (First Level). The coins associated with the First and Second Levels of the site cannot be assigned to a particular level, but they range in date from Ptolemy IV (222–204 BCE) to Hadrian (118–136 CE).[20] The arched barrel vaults also appear in a later house within the same block at Soknopaiou Nesos (I.108) and in two rooms of house C67 at Karanis. At the latter, a squinch vault was also used in an adjacent room.

The squinch vault and arched barrel vault both clearly have long pedigrees traceable to the Near East. This is not to say that they did not exist in pharoanic Egypt, but thus far I have found no record of them. At Karanis the two types were used by the same builders (presumably) but for different conditions: the arched barrel vault for long, narrow rooms and the squinch vault for squarish rooms. Notably, there are no proven examples in the Fayum of pitched brick sail vaults with the brick laid across the corners, which is the form that appeared alongside the parallel type in the earliest fired brick sail vaults outside of Roman Egypt (see the later discussion).

The sail vault eventually led to the Byzantine development of the dome on pendentives, so before



47. North Baths at Karanis, Egypt (date unknown). Author's sketch of *tepidarium* vault consisting of squinch vault supporting the radial brick dome. Inset shows detail of spring of vault over stone lintel of doorway (based on photographs from El-Nassery et al. 1976: pl. 40 figs. 17, 20).

leaving Roman Egypt, it is worth looking at another type of experimentation with new vault forms. The North Baths at Karanis, which were excavated in the 1970s by a French and Egyptian team, have a partially preserved vault over the *tepidarium* consisting of a small dome (0.80 m dia) atop a shallow sail vault (1.5 × 2.2 m) (Fig. 47). Unfortunately the excavators found no evidence that could provide a date for the building, though it apparently continued in use into the fourth century with various modifications along the way.[21] The low sail vault is made of pitched bricks (24 × 24 × 6 cm) set parallel to each of the four walls, whereas the dome is built of smaller bricks (24 × 12 × 6 cm) set radially, so there is a clear break in form and pattern between the two vaults. Such combining of different vault forms is rare, but R. F. Hoddinott notes something similar in a late third-century CE tomb outside of Varna (ancient Odessus), Bulgaria, when he describes a vault (3 m square) that is "cross-groined, except that the center was occupied by a regular domed apex measuring only 70 by 80 centimeters, in which vertically placed tiles were arranged diagonally across the angles."[22] These examples at Karanis and in Bulgaria represent the type of experimentation that eventually led to the Byzantine combination of a dome on pendentives. However, both the examples at Karanis and Varna are quite small and are probably the results of solving constructional issues, whereas the creation of the dome on pendentives used in Byzantine churches was based on a more complex theoretical idea about the relationship between geometry and interior space.

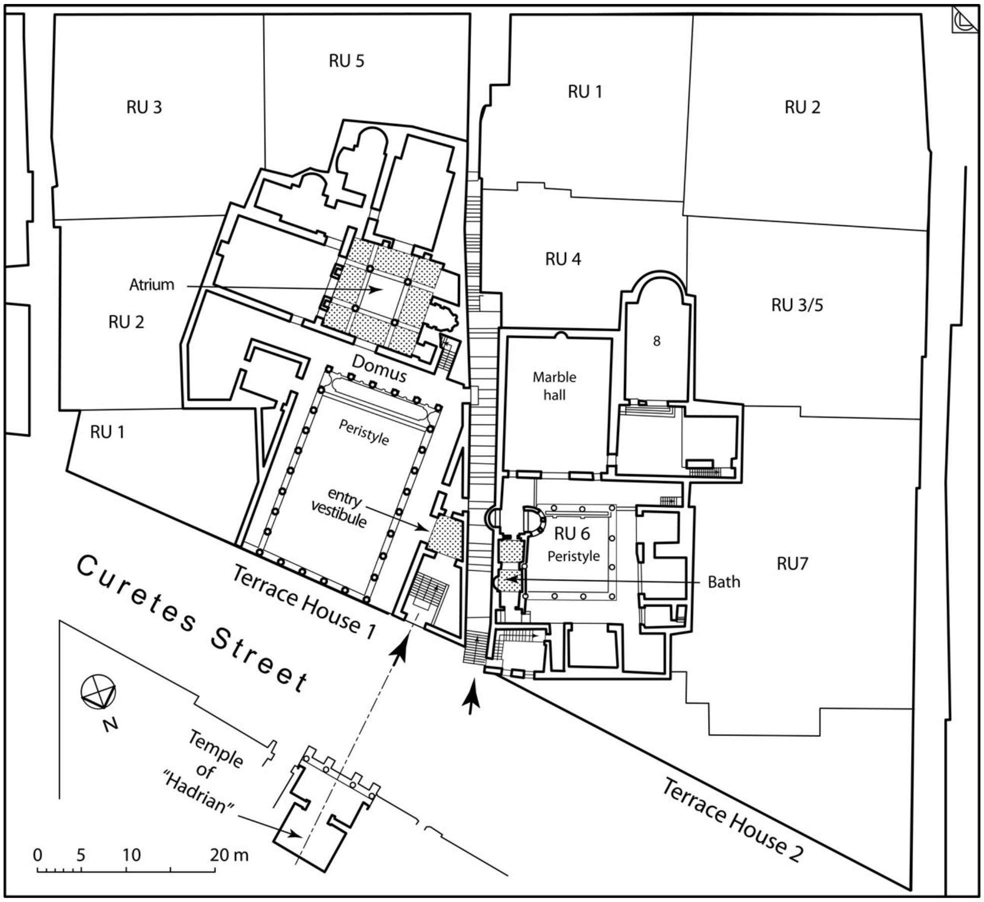
This overview of vault development in the Fayum shows that the fully developed sail vault with radially laid brick courses appeared at Soknopaiou Nesos probably by the Augustan period. This coincides roughly with the earliest known cut stone sail vault, which occurs in a bath at Petra, originally dated by J. McKenzie to the second half of the first century

48. Terrace House 1 at Ephesus (mid-second century CE). Upper stair vestibule of Domus with sail vault built using the fan method of laying the bricks.

BCE based on a comparison with the molding types of the Khasneh and Kasr el Bint. However, recent excavations at the Khasneh suggest that its moldings should now be assigned to the reign of the Nabatean King Aretas IV (9 BCE–40 CE), which in turn could imply a slightly later date for the bath in the early first century CE.[23] McKenzie's early dating of the Petra bath has been called into question largely based on the presence of the sail vault, which was thought to have originated in the second century CE,[24] but the Fayum examples demonstrate that the Petra vault is not as much of a chronological outlier as once thought. Moreover, a sail vault of *opus caementicium* (5.5 × 8.0 m) in Italy at the Julio-Claudian villa of Minori on the Amalfi coast[25] indicates that the form was employed in at least three different areas by the first half of the first century CE (WebCat. 4-C).

FIRED BRICK SAIL VAULTS OUTSIDE ROMAN EGYPT

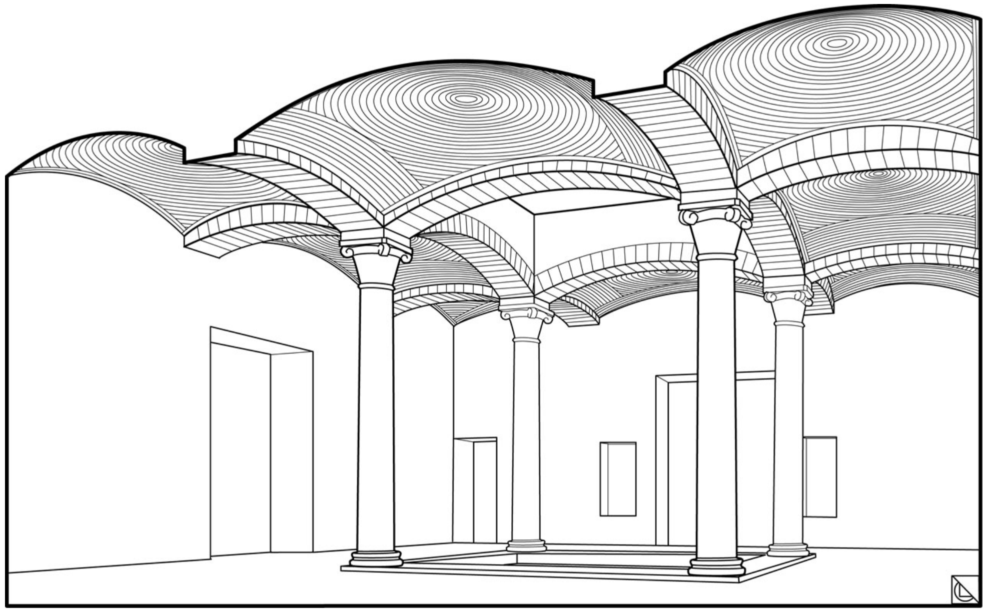
Sail vaults employing a combination of pitched and radial brick (always fired) appeared outside of Egypt by the second half of the second century CE. As at Karanis, some are built with pitched brick laid parallel to the walls, but a new pattern was also introduced where the pitched arches were laid in a fan pattern across the corners of the room (Fig. 48). The earliest examples that can be reliably dated occur at Ephesus where the sail vault was used in renovations at both Terrace House 1 and 2 (Fig. 49). The largest unit in Terrace House 1, referred to simply as the "Domus," consisted of a large peristyle that led into an atrium. Because the peristyle was significantly higher than street level, it was entered via a stair from Curetes Street that led up to a trapezoidal-shaped entry vestibule covered by a sail vault (4.5 × 4.2 × 4.2 × 2.7 m) built of fanned arches across the corners (Fig. 48). Instead of meeting at a joint in the center, a new series of pitched arches was built between them creating a multiple fan pattern. C. Lang-Auinger suggests that this vaulting technique was likely employed in the vestibule vault to deal with the difficult situation of having to build a low-rising vault over a trapezoidal space.[26] If so, it would represent an innovation that resulted from a modification of an existing technique (pitched brick laid parallel to the wall)



49. Plan of Terrace Houses at Ephesus with locations of brick sail vaults stippled.

applied in response to a particularly awkward set of conditions.

In the same renovation, the atrium of the Domus received a new roof structure that was not like any atrium in Rome or Pompeii; it consisted of a series of shallow sail vaults filling each of the eight bays around the *impluvium*. These vaults are much less well preserved than the entry vestibule, but enough remains to show that the springings were built of pitched bricks aligned parallel to the walls (WebFig. 17). Originally they were supported on the inner side by a column placed at each corner of the *impluvium* (Fig. 50). The columns were connected to adjacent walls by arches of radially laid brick, which would have been built using wooden centering, and each bay was covered by a shallow brick sail vault. Both the southeast and southwest corner bays (2.3 × 2.5 m) have pitched arches running parallel to the south (back) wall. The wider middle bay on the south wall (2.3 × 4.1 m) has the springing of parallel pitched arches remaining along its east side, but nothing more is preserved. Given the oblique alignment of the south wall, these three bays were trapezoidal in form. The arrangement of the sail vaults forming the atrium roof at Terrace House 1 is structurally more sophisticated than the mud brick cellar vaults in the Fayum because each vault is supported on at least one corner by a column. The columns supporting the vaults were stabilized – each line of support arches ended in one of the side walls, which provided the abutment to



50. Author's drawing of the vaulted atrium in the Domus of Terrace House 1 at Ephesus looking south (based on the reconstruction in Lang-Auinger 1996: Abb. 11, 80). Only the spring of a few vaults remain (WebFig. 17), so I have reconstructed the radial brick at the crown based on the preserved remains of similar vaults at the West Mausoleum at Side (Fig. 52).

absorb the lateral thrusts. Centering would have been used for the arches, but little to no centering would have been necessary for the vaults themselves. Once the vaults were added they formed a self-contained structural system bounded by four walls. The renovation phase to which these vaults belong has been dated to the third quarter of the second century based on the style of the capitals that supported the atrium vaults, sculpture found in situ, as well as excavated pottery in both the atrium and the vaulted vestibule.[27]

The plan of the Domus at Terrace House 1 reveals that the spaces all consist of rather grand reception rooms with no sign of *cubicula* or other private rooms. The excavators thus suggest a functional change from a private domus to a more semi-private use for banqueting, possibly for groups associated with the owner, such as a college of priests. Its prime location along Curetes Street with its impressive new entrance stair is directly across from the so-called Temple of Hadrian and the Scholastica Baths (also known as the Baths of Varius); its placement has led to the speculation that the Domus may have been owned originally by P. Varius Quintilius Valens (active during the first third of the second century CE) and that the renovations were made by his descendants as the family's prestige continued to rise.[28]

Pitched brick sail vaults also occur in the renovations of one of the units in Terrace House 2, Residential Unit 6 (RU6), which underwent various modifications during the second and early third centuries. Originally it was entered from the side alley, but in the Hadrianic period the entry was moved so that it was on Curetes Street, as was the one to the Terrace House 1 Domus. After climbing a flight of stairs one entered into a peristyle that originally had porticoes on all four sides, but during the renovation a small bath was built into the east portico (Fig. 51, WebFig. 18). The baths in their present form are covered by pitched brick vaults (2.1 × 2.4 m), which H. Thür has

51. Peristyle of Residential Unit 6 in Terrace House 2 at Ephesus showing original portico infilled for the addition of a bath suite. Arrow indicates location of inset photo of the fan sail vault. Note the crack in the middle of the vault.

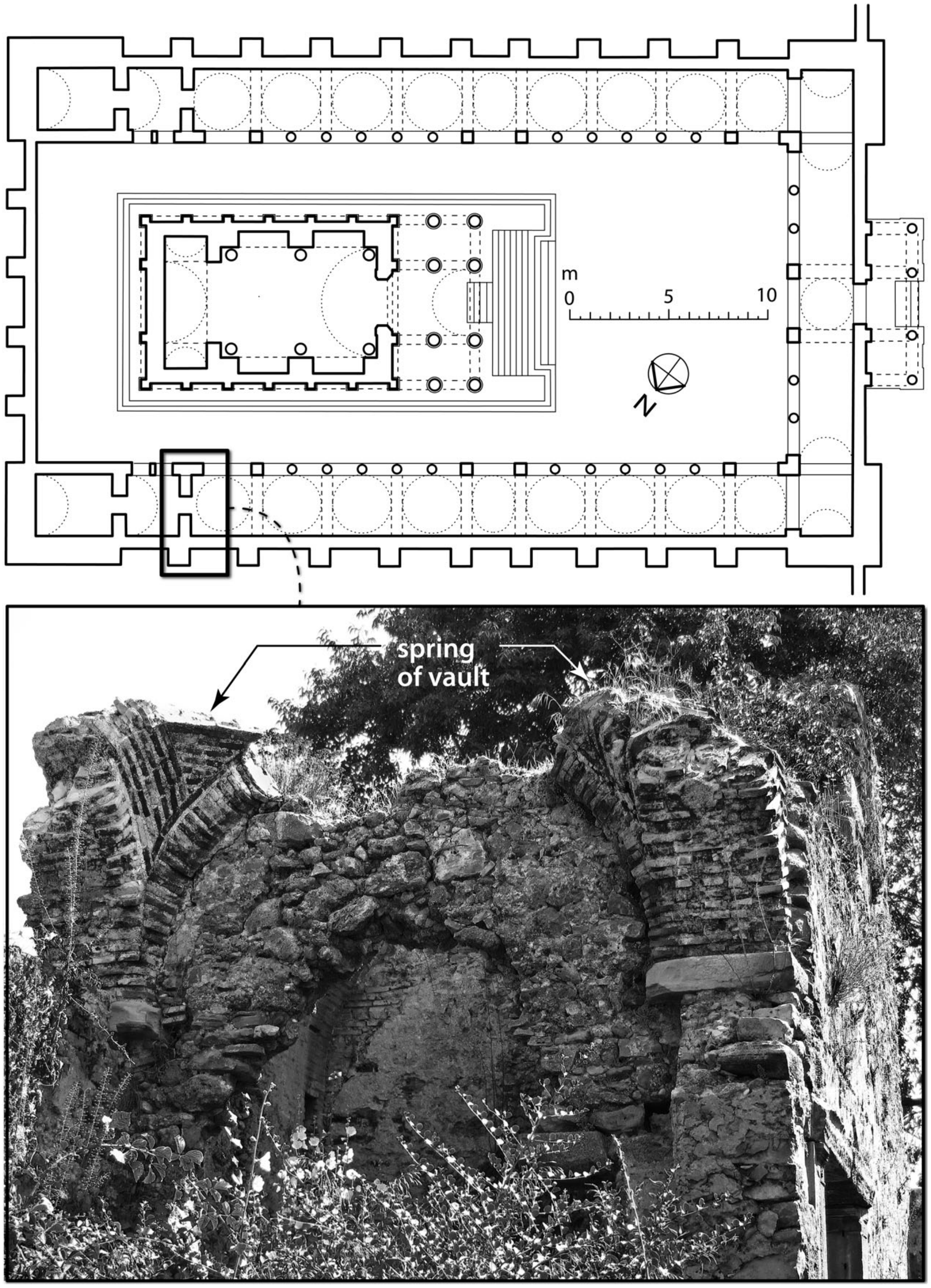
dated to the late Severan period.[29] The bricks were laid across the corners in the fan pattern so that the arches intersected along the centerline of the vault. The vaults had very little buttressing other than the columns and the added masonry. Nevertheless, they survived numerous earthquakes, though the crack at the crown, which zigzags its way through the mortar joints, shows that the abutments shifted at some point.

The living units with the pitched brick sail vaults in the Terrace Houses at Ephesus were among the most prestigious urban residences in the city, as is obvious from their location, size, and appointments (the wooden ceiling beams of the large, marble revetted *triclinum* in RU6 of Terrace House 2 were gilt!).[30] The owner of RU6 during the mid- second century was Gaius Flavius Furius Aptus, a member of a well-known family in Ephesus and a priest of Dionysus.[31] The renovations that took place during his ownership converted an already elegant and expanded town house into one with more palatial pretensions for the reception of guests. The addition of the vaults to the bath may well have been made by one of his descendants. The bath itself is quite small, but the vaulting represents a structural challenge given that it is built within the preexisting portico with very little buttressing. The Domus in Terrace House 1 is less well preserved and its owner less securely identified, but its size and context indicate that the person who owned it must have been a wealthy and powerful person within the city. Moreover, the decision to create a new type of vaulted atrium employing brick sail vaults was a bold one that reflects access to a creative architect and skilled builders using the latest vaulting technique in a very innovative manner.

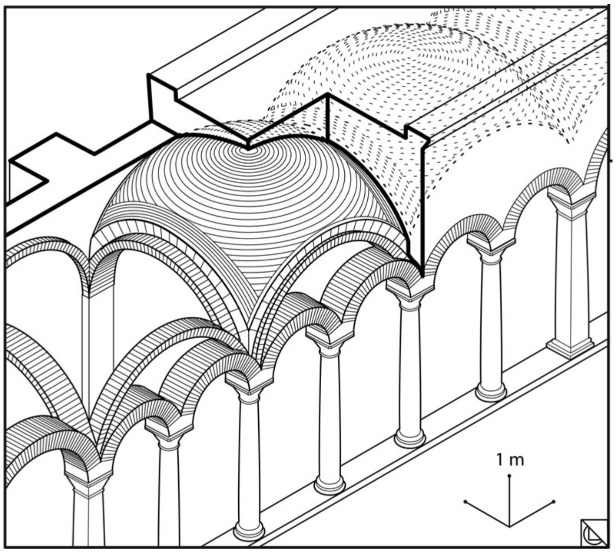
Elsewhere in Asia Minor at Side, some of the most inventive brick sail vaults also occur in wealthy private contexts, but in tombs rather than houses. Unfortunately, their dates are ambiguous. The first is an elaborate mausoleum complex in the west necropolis where brick sail vaults formed the roofing of the portico surrounding a temple-tomb (Fig. 52). A. M. Mansel reconstructed the two end bays and the central bay of the portico as supported along the front (inner) wall by piers and the other bays as divided into two parts and supported by columns spanned by arches (Fig. 53). The piers/columns no longer exist, but Mansel determined their locations from the pour channels remaining in the stylobate.[32] That the builders were concerned about the potential lateral thrust of the vaults is demonstrated by the series of buttressing piers aligned with the spring of the vaults along the back (outer) wall of the two side porticos. The existing remains of the sail vaults occur at the two back corners of the enclosure adjacent to the barrel-vaulted rooms. Both have six to eight courses of pitched bricks laid parallel to the back wall, with only one course along the side wall. The rest of the vault was built with radially laid bricks, a few courses of which remain in each of the two vaults (Fig. 52). As noted elsewhere, using sail vaults built of brick, rather than mortared rubble, would have allowed the builders to employ only minimal centering, mainly for the arches connecting the columns and separating the vaults.

The vaults of the portico of the West Mausoleum at Side are particularly revealing from a structural perspective because they were partially supported by columns. Unlike the vaults in the Domus at Terrace House 1 at Ephesus, they did not benefit from the cross-bracing of a grid configuration. They were more similar to the little bath in Terrace House 2, but at Side the situation represents the original design rather than a later insertion. In Rome, when concrete vaults were built on columned porticoes, iron tie bars were used to stabilize the structure during construction and to resist any lateral thrusts on the columns, as occurred at the Basilica Ulpia and the *palaestra* vaults of the imperial thermae. At Hadrian's Villa, a different method was used to ensure the stability of portico vaults – they were supported on columns or piers connected by brick lintel arches reinforced with iron bars.[33] At Side, by having some of the sail vaults supported on two arches rather than one, the builders allowed for more walling above the columns, which would have acted as surcharge to direct the lateral thrust downward. The additional columns would have also spread the forces more evenly along the portico (see Chapter 8). These builders seem to have had a sophisticated understanding of the structural behavior of their vaults.

Unfortunately, the date of the West Mausoleum is unclear. Proposals range from around 170 CE to the second half of the third century. A. M. Mansel originally dated the complex to the second half of the third century based on stylistic comparison of the architectural details, including the similarity of the vault construction to that at the Mausoleum of Diocletian at Split;[34] however, he was unaware of the earlier example at Ephesus, and, as we see later, the West Mausoleum has more in common with the atrium of the Terrace House 1 Domus than with the Mausoleum of Diocletian. Earlier dates have been proposed based on the stylistic analysis of portraits and sarcophagus fragments found in the tomb as well as of the architectural decoration. The earliest of the portraits found in the tomb is of a draped female with a hairstyle similar to Faustina the Younger and has been dated to c. 170 CE. Another is of a youth with a hairstyle that has been dated to the second



52. Plan of West Mausoleum at Side, Turkey, with a photo of remains of one of the sail vaults that once covered the north portico (plan based on reconstruction in Mansel 1963: Abb. 146).

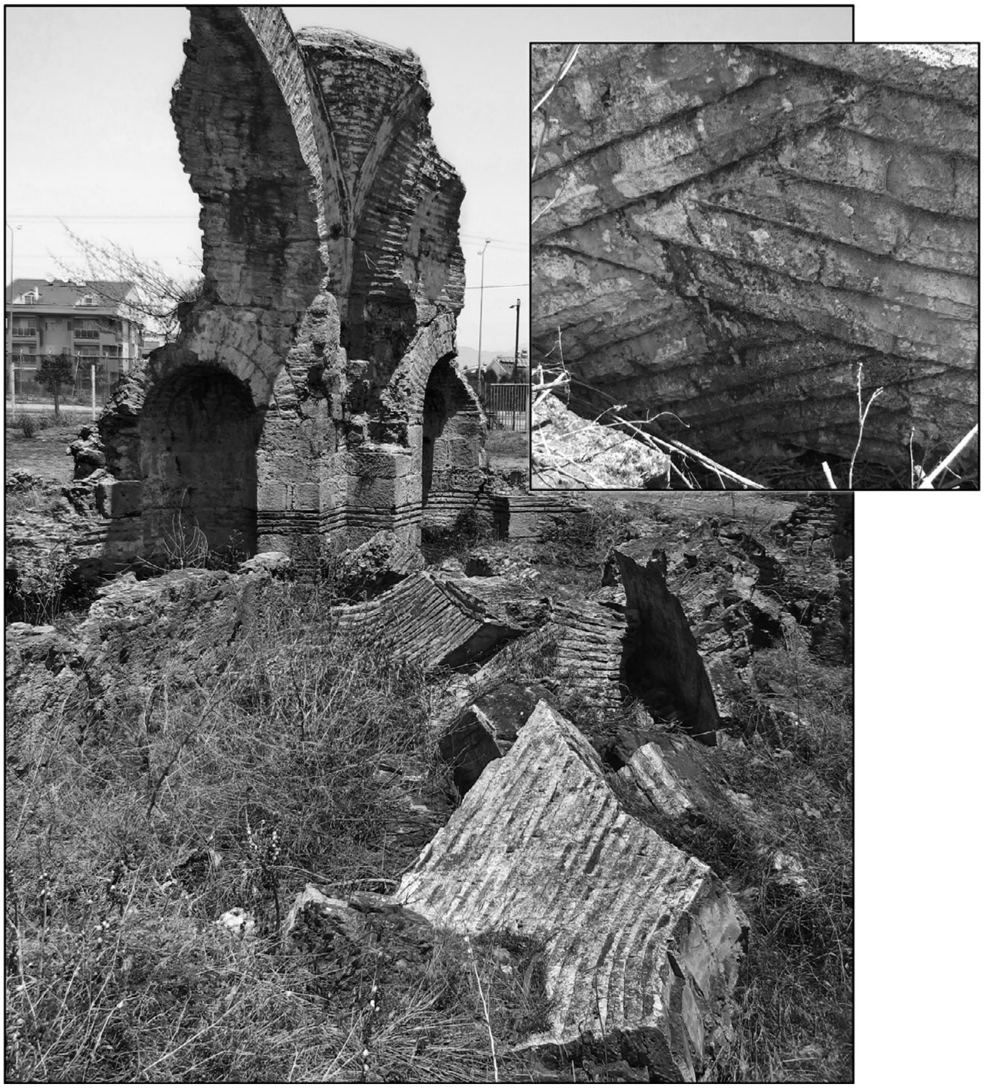


53. West Mausoleum at Side, Turkey. Author's reconstruction of the structural scheme of the sail vaults covering the side porticos.

quarter of the third century. He wears an unusual headband that may be the insignia of a priesthood of some sort.[35] The sarcophagus fragments have been dated alternatively to 160–175 or 195 CE.[36] J. Kramer dated the architectural decorations to the latter half of the second or early third century CE based on comparisons to other Pamphylian monuments,[37] but more recently C. Gliwitzky argues that the style of the architectural ornament indicates a later date in the second half of the third century.[38] Clearly, a different class of evidence is needed to resolve the dating issue.

In a tomb in the east necropolis of Side, a pitched brick sail vault employing the fan technique covered the central room (5.35 × 6.25 m), which had an exedra on each side. Today much of the vaulting lies fallen on the ground with only the pendentives remaining in place (Fig. 54), but more was standing in the 1960s as shown by published photographs.[39] Mansel suggested a date for the tomb of the early fifth century CE, admitting there was little dating evidence beyond the architectural form and the construction methods.[40] However, this form of vaulted tomb was used earlier at the mausoleum at Sardis containing the sarcophagus of Claudia Antonia Sabina (late second century CE). The tomb had a central rectangular room with exedrae on three sides, and the excavated remains suggest a mortared rubble vault.[41] Interestingly, the East Tomb at Side contained a sarcophagus decorated with *erotes* that has also been dated stylistically to the second half of the second century CE.[42] For the tomb itself, Mansel also used the fan construction of the vault as a dating criterion comparing it to the Baptistry of Mary at Ephesus and the crypt at St. Demetrius at Thessaloniki (Fig. 64C), but as seen at Terrace House 1 at Ephesus, the fan technique was used by the mid-second century. Nevertheless, another aspect of the tomb's construction may point to a late date: the bricks and mortar joints in the main vault were carefully shaped (Fig. 54) and the bricks in the niches were laid in a decorative manner (WebFig. 23), a treatment more typical during the fourth and fifth centuries.

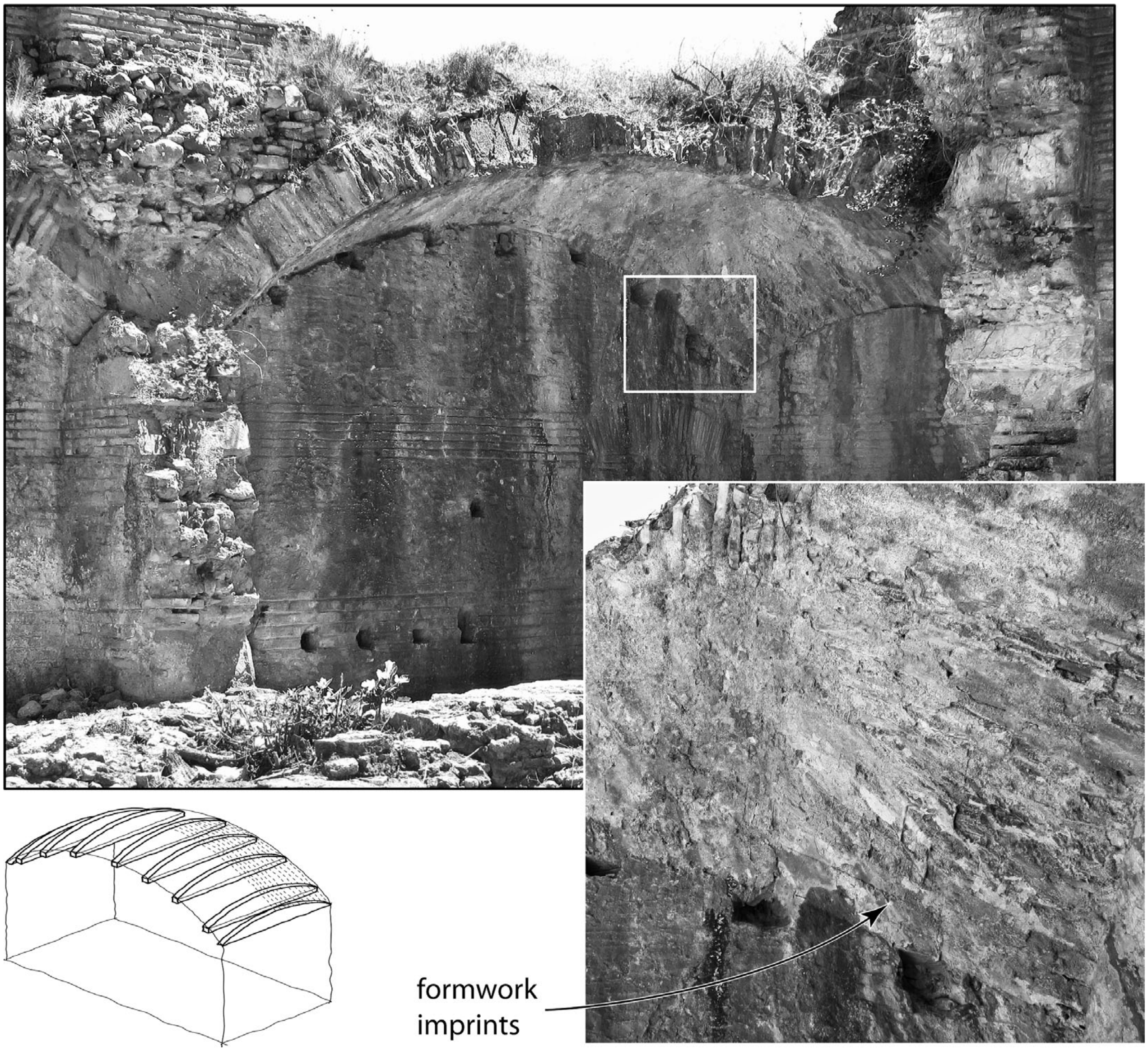
One other example of brick sail vaults in Asia Minor, at the Small Baths at Aspendus, is worth mentioning because it employs a hybrid technique different from both the radial and pitched techniques examined thus far. This technique occurs in two vaults over small rectangular rooms (3.5 × 5.5 m) between the main bathing rooms. On each side of the vault, the bricks were laid radially so that they intersected along the diagonal without forming a groin (Fig. 55, WebFig. 19). This was a fairly typical method of building brick groin vaults (as at the Leonidaion Baths at Olympia (WebFig. 20)), but this is the earliest example I know where it was used for a sail vault. Centering was clearly used because the holes for the centering beams remain on the long side walls and the imprints of formwork boards are visible in the remains of the vault itself. The centering for these vaults was apparently much less complex than for a cross vault. Each beam would have supported a very shallow arch form, and then boards (either short



54. East Tomb at Side, Turkey. Photo showing the pendentive of the central sail vault in situ and the remains of the fallen sections of vault in foreground. Detail shows construction of the fan technique with carefully raked mortar joints.

or thin and bent) were placed over top. The resulting brick vault formed the shell for rubble fill above.

Pitched brick sail vaults are also known from Greece, with one example dating to the same general time period as the early ones at Ephesus. At the Northeast Baths in the Sanctuary of Asclepius at Epidaurus, one of the rooms was covered by a sail vault (3.2 × 3.7 m) with pitched brick courses set parallel to each of the four walls (Fig. 56, Web-Fig. 21). In his discussion of the sanctuary Pausanias notes that a wealthy Roman senator named Antoninus recently built a bath and a sanctuary to the gods called *epidotai*, among other structures.[43] The Northeast Baths are sometimes assumed to be the ones mentioned by Pausanias, though other potential candidates exist in the sanctuary. Fragments of roof tiles stamped with ΑΝΤΩΝΙΕΝ that attest to the activities of Antoninus have been found at various



55. Small Baths at Aspendus, Turkey (second century CE). Elongated brick sail vault. Centering holes are visible along spring of the long side. Detail with arrow shows the formwork imprints along the intrados. Sketch to left shows reconstruction of centering. (Color image: WebFig. 19).

locations within the sanctuary (but not actually in the Northeast Baths).[44] Pausanias's Antoninus has been identified as the wealthy benefactor, Sextus Julius Maior Antoninus Pythodorus from Nysa, who was in the circle of Aelius Aristides and is known from an inscription at the Sanctuary of Asclepius at Pergamum.[45] As at Ephesus, the sponsor of the construction project here was likely a well-connected private benefactor.

At least two other examples of pitched brick sail vaults are known from Greece.[46] One occurs in an undated tomb (RG5) at Troezen (3.58 m span) and has the courses set parallel to the wall with the joint between them running along the diagonals.[47]

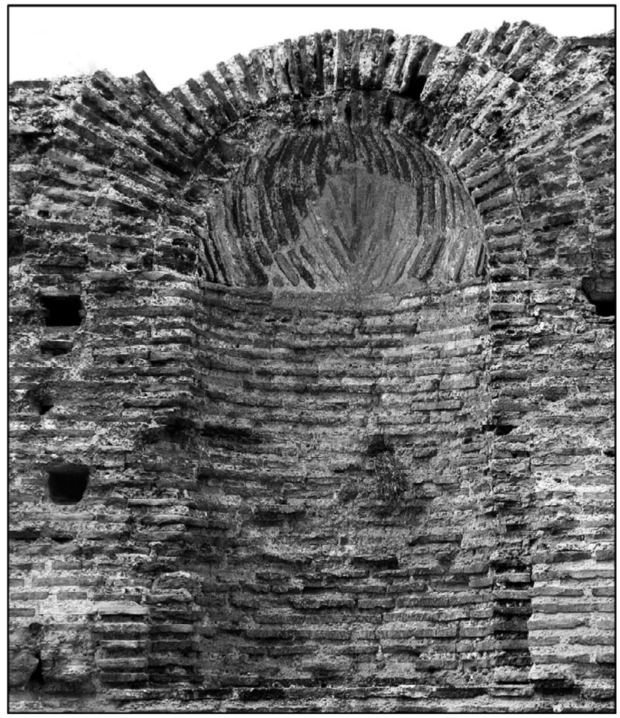
56. Northeast Baths in Sanctuary of Asclepius at Epidaurus, Greece (mid-second century CE). Pool of *frigidarium* covered by sail vault with remains of pendentive in inset. Note also the pitched brick construction of the semidome of the niche in the back wall. (Color image: WebFig. 21).

Another is a ten-sided structure at Riza in Epirus (7 m dia.; dated by pottery to third–fourth century CE). Only the springs of the vault remain in some of the corners, which indicate that it was constructed similarly to the four-sided sail vaults with courses laid parallel to the walls. The structure was probably part of a bath complex possibly attached to a wealthy villa outside of Nicopolis.[48] The Roman vaulting in Greece has been understudied until recently, [49] and further investigation may well turn up more examples.

PITCHED BRICK DOMES AND SEMIDOMES

The pitched brick vaults examined so far have the bricks laid either parallel to straight walls or across the corners; the difficulty in translating the technique to a dome or semidome is that neither has straight walls or corners. The initial attempts at using the pitched brick technique for semidomes seem to have occurred in small niches. The earliest I have found is at the Northeast Baths at Epidaurus in a small niche (90 cm wide) in the back wall of the room with the pitched brick sail vault, where the bricks are set in segments that radiate up to form a V-shape (Fig. 56, WebFig. 21). Experiments in how to resolve this issue can be seen in various other monuments, most notably under the Tetrarchs at the turn of the third to the fourth century. In two niches in the exterior wall of the Rotunda of Galerius (St. George) in Thessaloniki (306 CE), the semidome consisted of a shallow sail vault with the lunettes filled with brick walling that followed the curvature of the vault (Fig. 57). The builders probably built the curving lunettes first and used them as the base for the pitched brick

57. Rotunda of Galerius at Thessaloniki (early fourth century CE). Exterior niche with pitched brick along intrados.

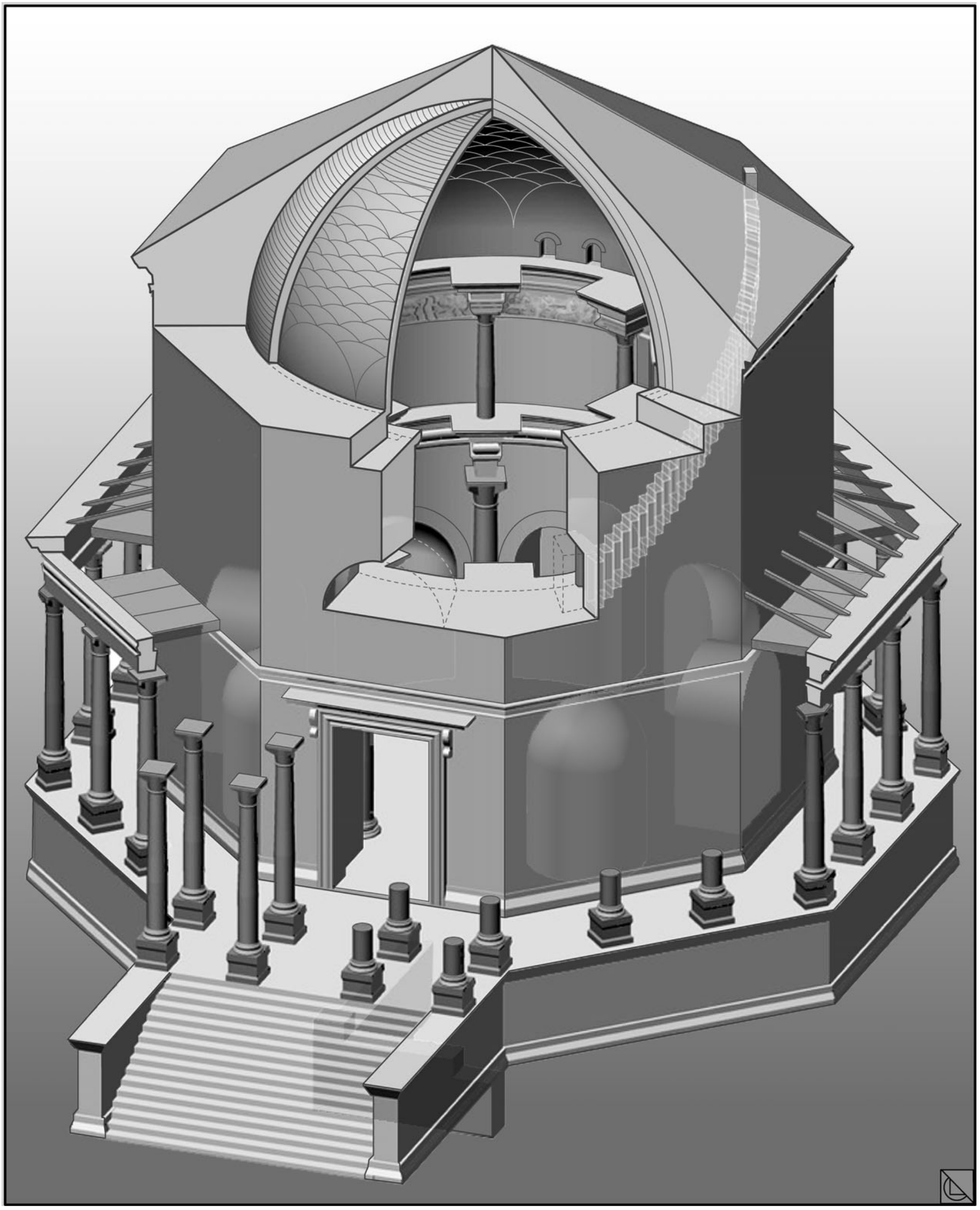


58. Niche at Palace of Galerius at Thessaloniki (early fourth century CE). Note that the inner brick shell of small, pitched brick forms the permanent centering for two additional layers of larger, radial brick shells.

59. Palace of Galerius at Gamzigrad, Serbia (ancient Felix Romuliana) (early fourth century CE). Photo of sail vault from one of the towers of the fortification walls (photo: Ulrike Wulf-Rheidt).

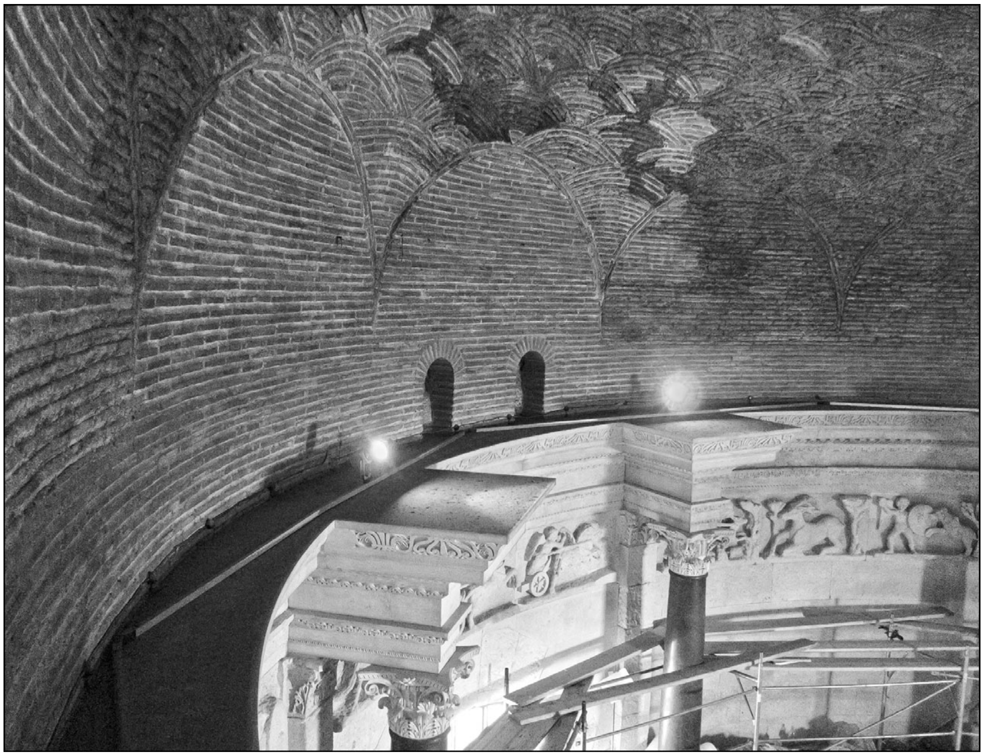
above. The process would have required only a string or rod to lay out the curve and would have eliminated the centering altogether. Nearby, in the remains of the rooms of the palace, a completely different approach can be seen. A lining of very narrow pitched bricks was created by laying them in opposite directions so that they meet in the center (Fig. 58). A radial arch of larger bricks was then built above this permanent centering of small bricks. At Galerius's other palace (298–311 CE) at Gamzigrad (ancient Felix Romuliana) in Serbia, a pitched brick vault covers the circular space of the fortification tower at the southwest corner (Fig. 59). Given the relative rarity of the technique, its use at both places may indicate an imperial building squad working on imperial projects.

The monument with the most masterful resolution to using pitched brick for a vault with no angles is the Mausoleum of Diocletian at Split (c. 305 CE). The building is circular on the interior and octagonal on the exterior, surrounded by an octagonal colonnade with a pedimented entrance on one side (Fig. 60). At first glance, the dome (13.4 m span) appears to be a



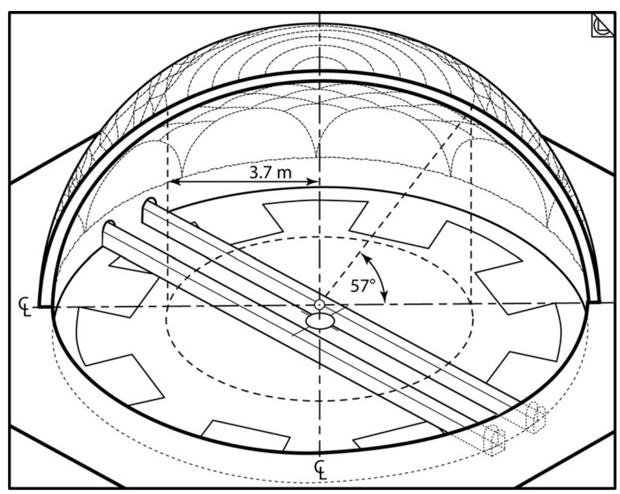
60. Mausoleum of Diocletian at Split, Croatia (c. 305 CE). Author's semi-transparent cutaway axonometric drawing showing the two layers of the brick dome with the inner shell employing the fan method in the lower part and the outer shell of radial brick, as well as the staircase built into the outer wall leading to the roof. Note that the pitch of the roof shown is the original version proposed by G. Nikšić (2004: fig. 2), rather than the higher modified version on the building today.

twelve-sided sail vault because it sits on twelve arches (3.5 m wide) between which spring pendentives. But as with the niche at the Rotunda of Galerius, the pendentives are not spanning corners, but rather the lunettes underneath were built to the curve of the dome. (This design in itself was not new because the Pantheon has arches built into the curving portion of the dome.) In this manner, the arches created curving



61. Mausoleum of Diocletian at Split, Croatia (c. 305 CE). View of the fan construction of the dome and the two (beam?) holes above the cornice.

triangular gaps between them that were filled with the first layer of pitched brick arches (i.e., the "pendentives"; Figs. 60, 61). When these spandrels were filled, the top of the partially completely dome had a scalloped form with V-shaped dips in which were laid the subsequent layers of fanned arches. These dips allowed the fan technique to continue upward. At a point about 41° from the impost, the builders found that the dips were becoming too shallow to support further fans of arches, so they made the next fan cover two of the lower ones, thus creating a series of larger dips from which to continue laying the pitched arches. The fan pattern continues upward to about 57° from the impost, and then the crown is completely filled with radially laid brick, covering a diameter of 7.4 m (Fig. 62).



62. Mausoleum of Diocletian at Split, Croatia (c. 305 CE). Drawing showing the holes above the cornice with beams spanning the space and the location of the center point of dome from which lines could be used to lay out the form. The dotted line shows the area where centering would have been needed for the radially laid brick at the crown.

Using the pitched brick eliminated the need for elaborate centering, but the domical form still had to be laid out, and the uppermost section at the crown, which was laid radially, would have probably required some support during construction. Evidence for how these tasks might have been accomplished is preserved at the base of the vault itself. Above the entrance is a pair of large holes (c. 75–80 cm high, 40–45 cm wide, 33 cm deep) spaced about a meter apart with another corresponding pair directly across from them (Figs. 61, 62).[50] They are set directly onto the cornice and are carefully built with arches forming the tops. Given the similar large holes at the base of barrel vaults (Chapter 3, Fig. 23), they were most likely used to secure beams that aided in the construction of the vault. The fact that there are two holes side by side rather than a single one suggests that the beams were meant to support an elevated platform, or bridge, stretching from one side to the other. In barrel vaults the holes at the impost were evenly placed along the length of the support walls, so one wonders why a wooden structure would be built across the middle of the dome rather than along the walls. The pitched brick technique was clearly chosen to avoid using centering where possible, but even so the curve of the dome had to be determined; the most likely method would have been to stretch a line from the center point. One explanation for the "bridge" was that it allowed for the establishment of that center point, which lay almost 15 m above floor level (Fig. 62). The designer and builder were keenly attuned to the challenges of the building process, as demonstrated by the concealed staircase built into the upper level wall that gives access to the roof (Fig. 60). This staircase is not accessible from the ground floor, but only from the semicircular opening on the front face of the building where it may have been concealed by porch roofing, depending on how that missing part was originally constructed. It therefore must have played a role in the construction and maintenance of the building.

Another telling constructional detail is that the dome was built of two layers of brick, each using bricks 33 cm square. A test trench conducted on the exterior of the haunch of the dome revealed that only the interior brick shell was laid with pitched brick while the exterior one was laid in the normal radial manner (Fig. 60).[51] The most obvious reason for using two layers of small bricks is that larger bricks would have been much heavier to handle and likely to slide off if no centering was used. A typical *bipedalis* would have weighed as much as 25 kg.[52] The idea of using a pitched brick inner shell as the permanent centering for an outer radial brick shell can also be seen, at a much smaller scale, in the niches at the Palace of Galerius in Thessaloniki (Figs. 57, 58). One issue that the builders would have encountered in building such a large dome is that the inner pitched brick shell had to be thick enough to be self-supporting. As noted in Chapter 1, the maximum ratio for the dome thickness to free span is 1:49. The inner shell of the mausoleum comes just within this allowable ratio at 1:41.[53] However, the second shell was likely added as the first one was going up, so that the full hemispherical dome was never a single layer thick. The inner layer would then need to progress ahead of the outer layer by only a few courses. This process would have also aided in constructing the dome without centering by providing it with additional stability to support the men and materials as it rose.

Nothing exactly like the pitched brick dome of the Mausoleum of Diocletian was ever repeated, which raises the question of why it was attempted at all, given that other domes in the palace, albeit smaller, typically used a combination of small squared stones at the haunch with radial brick at the crown (WebFig. 22).[54] Likewise, the significantly larger dome of the Rotunda of Galerius in Thessaloniki (c. 23.1 span) was built of radial brick and even retains the holes

63. Mausoleum of Diocletian at Split, Croatia (c. 305 CE). The dome from below showing the fan construction and the spatial effect of the projecting cornice (photo: Goran Nikšić).

used for scaffolding. The mausoleum was different in that it had a highly decorative interior bound into the structure of the supporting walls that had to be protected during construction. One of the most startling aspects when one enters it today is the effect of the two projecting columnar orders and the massive cornices above that seem to fill the room (Figs. 60, 63). Unlike more typical schemes in which the columns support a continuous projecting cornice and at least appear to be providing support, here the columns do not even show a pretense of supporting anything at all. Using the pitched brick technique in the lower parts of the dome would have aided in reducing the amount of heavy timber work required within the relatively small space. The radial brick crown of the dome, which would have likely required at least some support at the very top, was within the central area where the cornices did not project

(Fig. 62). Like the trapezoidal space at the Domus of Terrace House 1 at Ephesus, the dome of the Mausoleum of Diocletian may represent the modification of an existing technique to aid in dealing with an unusual condition.

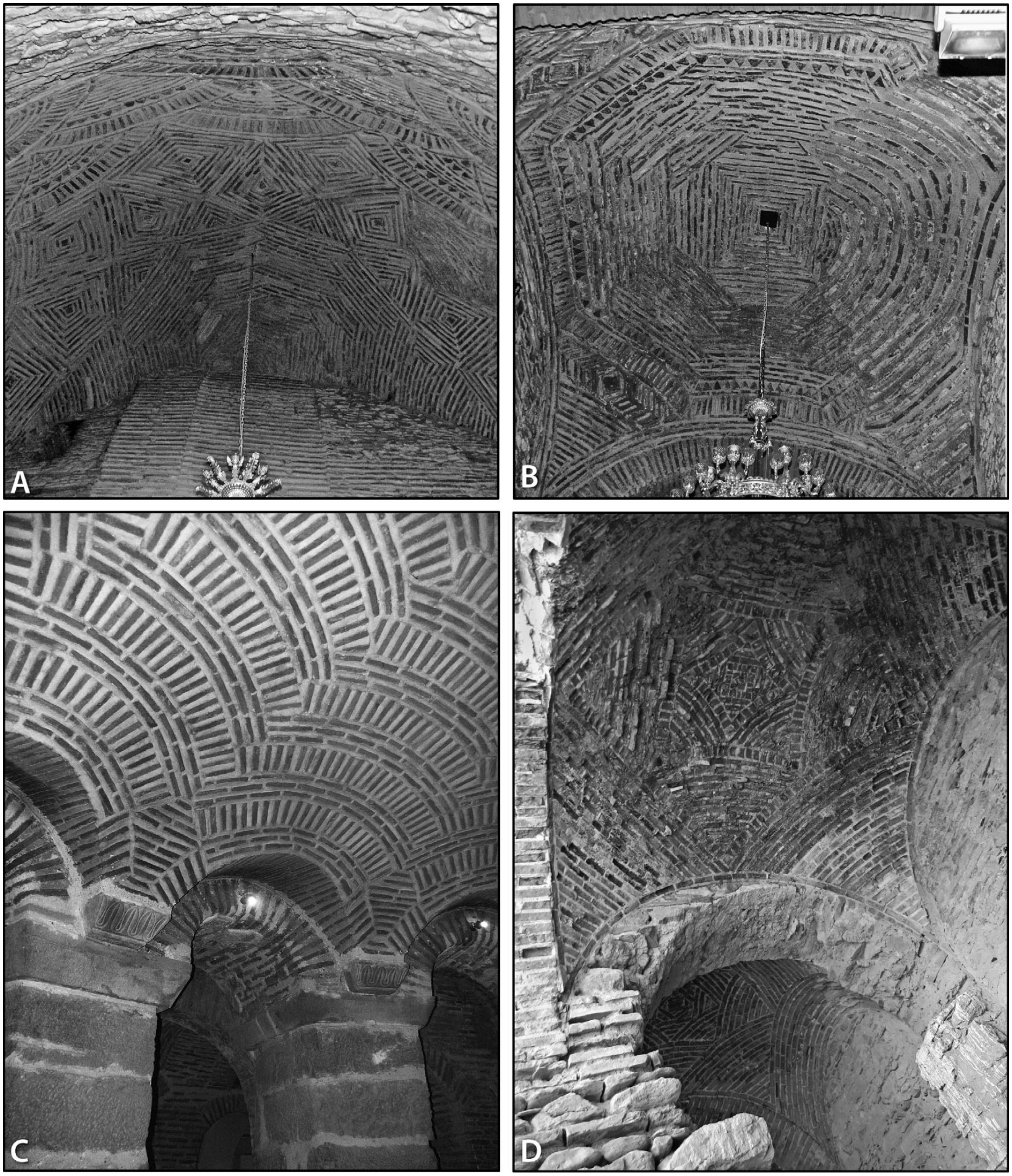
Domes and large semidomes rarely employed pitched brick, and the ones that can be dated are late. The only other dome springing from a cylinder known to have used pitched brick is the Baptistery of St. Mary at Ephesus (fourth/fifth century CE), where a single piece of fallen vault preserves the springing of the first row of arches.[55] The fan technique was also used for sail vaults at St. John in Ephesus (13.5 m span; sixth century CE) and for a sail vault (4.0 × 3.5 m) and two semidomes (6.5 and 8.8 m dia) at St. Demetrius in Thessaloniki (Figs. 64A, C).[56] An interesting aspect of two of the vaults at St. Demetrius (Figs. 64A–B),[57] is that the brick pattern was embellished with decorative patterns and special glazed tiles and was presumably meant to be seen. A similar decorative approach can be seen in a couple of sail vaults in an undated structure next to the theater at Nysa (Fig. 64D) and in the niches of the East Tomb at Side (WebFig. 23).[58] These examples display the virtuosity of the builders who applied the patterns in a fanciful manner that vied for the viewer's attention in the same way a geometric floor mosaic might. Finally, examples of the fan technique in Christian buildings can be seen in Greece in a fallen vault of the octagonal church at Philippi (c. 400 CE) and at the late tenth-century Monastery of St. Leontius at Vodiča outside of Strumica in the Republic of Macedonia.[59]

CONCLUSIONS

The pitched brick technique for building complex vault forms appears to have been an innovation of the Near East and central Asia. The pitched brick squinch vaults at Tell al Rimah from around 2000 BCE display an early understanding of the technique and seem to have been used in order to build without centering; the very shallow form of the vault suggests that the geometry of the form was not a determining factor. The remains of the first-century BCE squinch vault (9 m span) of the well house much further east at Delbarjīn in Afghanistan demonstrates the ability to use the technique at a much larger scale. The context in which the vault was used, to cover a wellhead, was part of a very large residence (84 × 58 m) that included a central reception room and garden court (compare the House of Faun at Pompeii at 81 × 32 m). It was clearly a very prestigious complex, possibly a palace, with its own private covered water source.[60]

The sail vault or a crude version of it, using corbeled and sloping (rather than truly radial) bricks/stones, goes back to at least the third millennium BCE in both Egypt and Mesopotamia, but it was first built in pitched brick in Roman Egypt. The earliest pitched method was to lay the bricks parallel to the walls. This type occurs at Karanis by the early second century CE. However, earlier sail vaults occur in radial mud bricks at Soknopaiou Nesos and in radially laid stone at Petra, so clearly the form was not a result of the method of construction applied.

Soknopaiou Nesos and Petra may at first seem an odd pairing to share the status of "earliest examples of." Like the other towns in the Fayum, Soknopaiou Nesos was mainly a poor farming village that had existed from the Hellenistic period, supplying food from its rich, irrigated oasis landscape. During the late Ptolemaic period, the irrigation systems had evidently begun to break down because Suetonius tells us that, once Egypt was brought under Roman control, Augustus sent in the military to reconstruct the irrigation system and thereby increase the grain supply for the *annona* (state grain supply).[61] After



64. Examples of decorative patterned use of pitched brick. A: Semidome at floor level of St. Demetrius at Thessaloniki. B: Sail vault at floor level of St. Demetrius at Thessaloniki. C: Crypt vault of St. Demetrius at Thessaloniki (reconstructed on model of original after fire damage). D: Sail vaults next to theater at Nysa, Turkey.

this intervention, the Fayum towns underwent a renaissance and new housing was built. The cellar vaults of the houses reveal experimentation in mud brick forms, but these towns are unlikely to represent the hotbeds of innovation.

Petra is a much more sophisticated urban site than any of the Fayum towns, yet it too had an unusual history during this period. It was the capital of the independent kingdom of the Nabateans, who were a nomadic people until the end of the second century BCE. Petra had long been a strategic Nabatean settlement because it controlled the caravan trade to the East. After the decline of the Seleucids and loss of territory to the Parthians during the last quarter of the second century BCE, the Nabateans gained power in the area and began to monumentalize Petra. Having existed largely as nomads, they had little architectural tradition of their own to draw on, so they adopted that of the Hellenistic kingdoms with which they traded, especially the Ptolemaic kingdom based at Alexandria.[62]

Little remains of any vaulting at Alexandria, but it is a likely source of inspiration for the vaults at both the Fayum and Petra. Alexandria was a center of political power in the eastern Mediterranean as well as an intellectual center formed around its famous library. That a sophisticated geometric form like the sail vault would appear in these two areas within the Alexandrian sphere of influence accords well with what we know from literary sources about the interest of mathematicians at Alexandria in applying geometric principles to vaulting. Heron of Alexandria, writing in the 60s CE, describes the geometry for placing a spherical vault over a square room.[63] The manuscript derives from a Byzantine copy, but as J. McKenzie points out, given the existence of sail vaults before Heron's time there is no reason to assume that this part of the manuscript was added later; moreover, she points to a work of Menelaus of Alexandria, *Sphaerica*, from the late first century CE in which he discusses triangles laid onto spheres, which would apply to the idea of the pendentive.[64] Thus, the growing popularity of the sail vault during the first century CE may well have been driven by an interest in geometric principles and their application to architecture.[65] Egypt, with its long history of mud brick vaulting, was a logical place to experiment with pitched brick techniques for this new vault form.

Sail vaults built of pitched (fired) brick appeared outside of Egypt for the first time at Ephesus and at Epidaurus just after the mid-second century CE. In the previous chapter I suggested that the idea for the earliest vertical brick vaulting in Greece was inspired by examples in Parthia and brought westward by the returning troops, but the same argument cannot be applied to the pitched brick sail vaults because they have precedents in Egypt but not in Parthia. The two vault types (vertical brick barrel vaults and pitched brick sail vaults) appear in Greece and Asia Minor at different times and in different contexts. Alexandria was home to Roman legionary bases, and a connection with Ephesus is possible because there would have always been some military presence in Ephesus accompanying the proconsul.[66] But direct evidence for the agency of the transmission of pitched brick sail vaults from Egypt to Greece and Asia Minor is difficult to isolate.

The earliest examples of pitched brick sail vaults occur in private contexts as opposed to public or imperial ones, which is a completely different situation from what we saw with vertical brick barrel vaults, which occurred mainly in public projects. The pitched brick sail vaults occur at Ephesus in private residences, at Side in a private mausoleum, and at Epidaurus in a bath building (privately funded?) within the Sanctuary of Aesclepius. We know very little about the person who owned the West

Mausoleum at Side, but he (or she) must have had access to substantial resources. Mansel found that the porticoed enclosure for the temple tomb was fronted by an even larger courtyard entered via a central portal framed by two towers, the whole of which faced onto the shore forming a quay wall for boat landings.[67] The size, decoration, construction, and setting all point toward the patron as being part of a very wealthy and powerful family in the region. The patron of the bath at Epidaurus was potentially Sextus Julius Maior Antoninus Pythodorus, and that for Terrace House 1 was possibly a member of the wealthy Varius family. The patrons of these projects were all members of the elite who would have had access to the most skilled architects and builders. Presumably there was some prestige value in creating new architectural forms using the latest methods available. Certainly in the case of the new vaulted atrium at Terrace House 1 or the porticoed mausoleum complex at Side, the patrons were making architectural statements. When the technique was adapted for use in domes and semidomes under the Tetrarchs, it was again used in "private" contexts, albeit imperial ones. The dome of the Mausoleum of Diocletian at Split presented unusual constructional challenges because of its unique interior design. Moreover, it was on a different scale from earlier examples. In Rome, one usually expects constructional innovations to occur in imperially sponsored projects and to trickle down (or not) to private contexts, but in the case of the pitched brick sail vault in the Greek East, the reverse seems to have been the case.

Regarding the technology shelf, let us return briefly for another look at that inscription discussed in Chapter 1 (p. 11; WebFig. 1), in which the builders asked the oracle of Apollo at Didyma for advice concerning problems on the job at the theater at Miletus. The inscription is found in the uppermost part of the theater, which is presumably where the job took place. The workers specified that the architect Menophilos had contracted with them to build a section of the theater. The words used to describe the work are εἰλήμα[τα] (*eilimata*) and τετραέτα (*tetraeta*), both of which are rare. J. Fontenrose translated them simply as "the arches and vaulting," whereas W. H. Buckler translated those words as "the arching and the vaulting over the columns," though columns are not specifically mentioned in the inscription.[68] Buckler's translation raises the image of the standard portico at the top of the cavea, albeit one covered with vaults instead of a timber roof. A variation, εἰλήμα (*eilima*), of the first word is also found in an inscription from Aphrodisias where it describes a building part, translated as an arch supported by "white marble pillars" (λευκολίθους παραστάδας, *leukolithous parastadas*),[69] which is where Buckler's idea for the columns originates. A similar phrase (εἰληματικαὶ καμάραι, *eilimatikai kamarai*) appears much later in a Byzantine manuscript of Constantine Porphyrogenitus (tenth century CE) describing the domical vault of the crypt under the Mausoleum of Diocletian and various domed churches in the region.[70] Because the buildings he describes are known, by this time the term clearly signifies a dome. The second term, τετραέτα (*tetraeta*), has been interpreted as a four-sided vault, like a cross vault or cloister vault, largely based on its etymology.[71]

Taken together, the implications of the two terms could very well describe something like what was built at the West Mausoleum at Side – a portico formed by a series of cross or sail vaults on columns or piers.[72] As explained earlier, this is a very challenging way to build because the portico provides little buttressing for the lateral thrust of the vaults, though the curved form of the portico would have provided some added stability (see Chapter 8). If this was indeed the type of portico these builders were trying to construct, it might explain why they ran into problems and were debating about breaking the contract, yet it would also suggest that the technique had not been fully mastered by the local builders.[73] Given the ambiguity of the language in the inscription and the complete destruction of the upper levels of the theater at Miletus, we will probably never know exactly what these builders were trying to do, but this was possibly a situation in which the technology shelf was mounted a bit beyond the reach of some of its users.

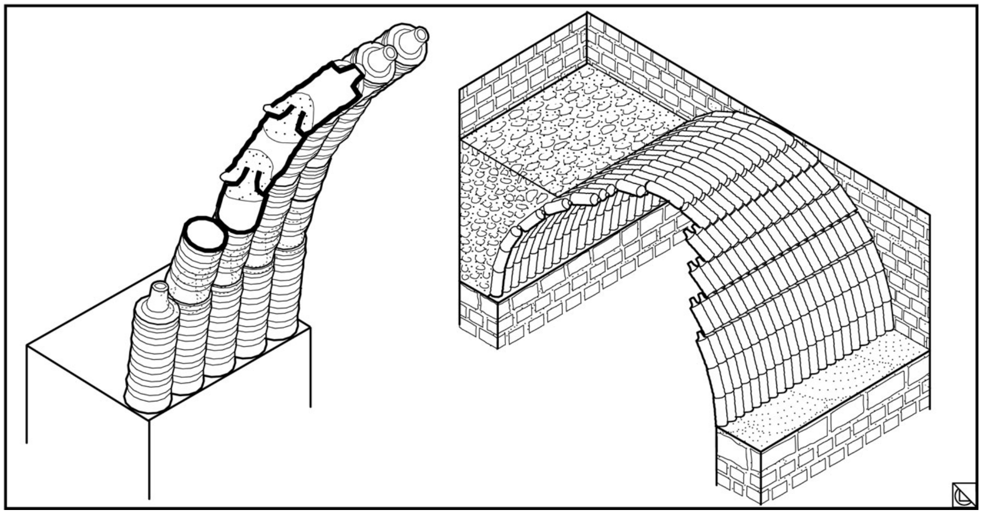
5

VAULTING TUBES

The technique of using terracotta tubes to build vaults dates back to the third century BCE, but its perfection and proliferation occurred many centuries later during the imperial period in North Africa.[1] As with pitched brick vaulting, its final manifestation was intended as a means of building vaults without using wooden centering (Fig. 65). It also shares with pitched brick some of the same advantages in creating complex forms with double curvature. In some earlier publications, the use of the vaulting tubes has been conflated with the use of empty amphoras in vaults,[2] but the two are entirely different techniques with different origins and intentions. Unlike the use of amphoras in vaults, which represents the use of recycled material made for a different purpose, the vaulting tubes were specially made items intended as constructional elements from their inception. I have dealt extensively with the reuse of amphoras in Rome elsewhere,[3] and because it occurs only occasionally in the provinces before the fourth century,[4] it is outside the focus of the present work. Here I deal exclusively with the use of terracotta tubes and small interlocking pots that form the intrados of vaults. The study of these vaulting elements demonstrates how the development of agriculture and the terracotta industry had a profound effect on both building construction and architectural style and how seaborne trade in agricultural products affected technology transfer and building construction.

Vaulting tubes have intrigued scholars since they were first recognized. There is a vast literature on their use in both North Africa and in early Christian buildings in Italy, but the two recent works on which much of my own study depends are the 1992 article by R. J. A. Wilson and the 1994 monograph on vaulting tubes by S. Storz. Wilson's work is shorter and is part of his broad interest in the archaeology of the western Mediterranean, especially Sicily and North Africa, whereas Storz's work is the result of years of study of this particular building technique in minute detail. Both were investigating the subject independently and have different insights to offer. I combined their respective catalogs of examples and added to it for a total of just over 150 sites and almost 375 different structures ranging from the third century BCE to the sixth century CE (Fig. 66, WebCat. 5-A); however, I focus on the development of the technique only up to the fourth century CE because the alterations that occur when it is applied in Christian contexts were affected by changes in government, economy, and social structure that go beyond the narrative of this study.

Catalogs (WebCat.) and color figures (WebFig.) can be downloaded at www.cambridge.org/vaulting

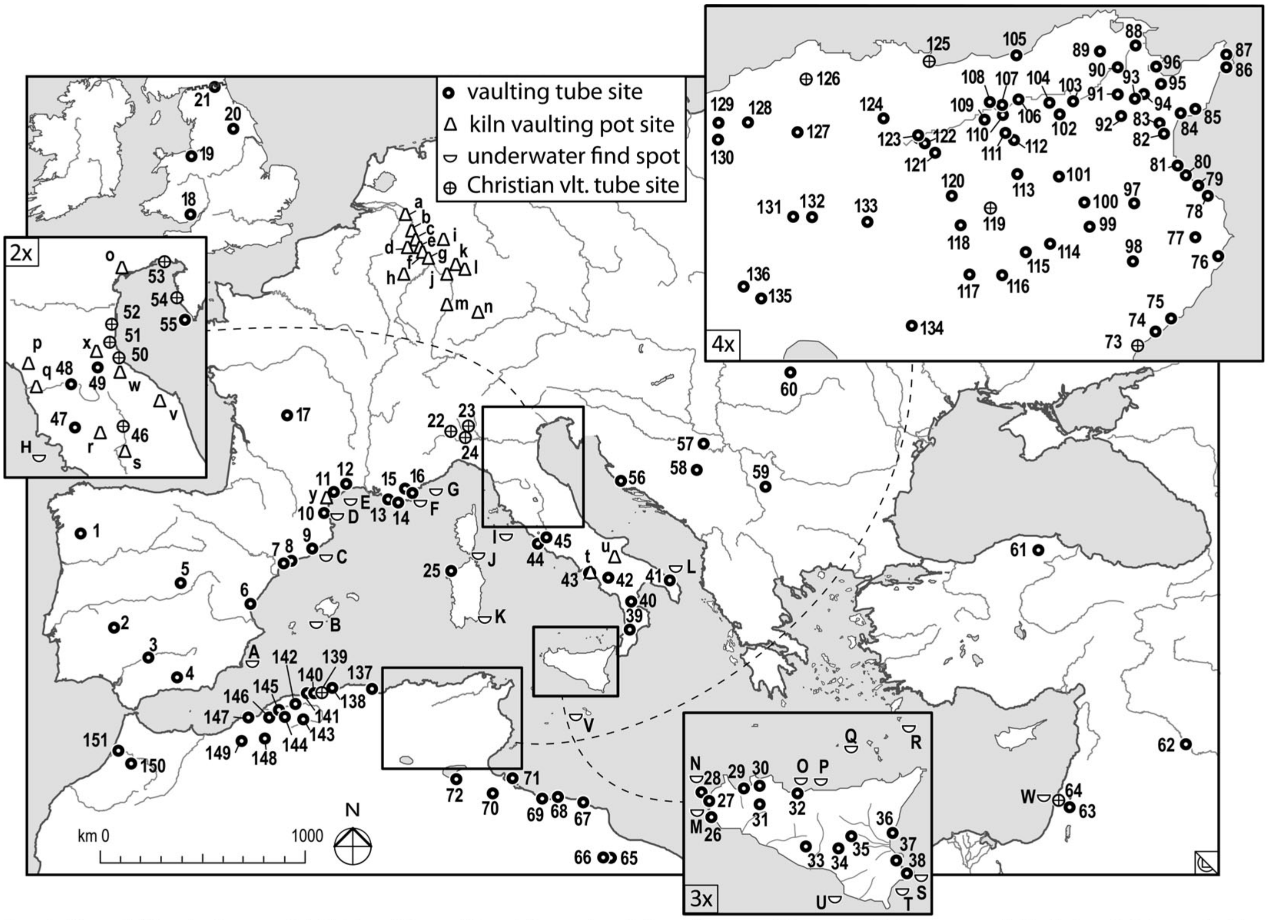


65. Reconstruction of barrel vault made of terracotta vaulting tubes.

The form of the vaulting tube underwent a long period of development during which it went from a large bullet-shaped tube to various forms of closed pot-like elements to the final version of a small tube with a distinctive nozzle at one end, as illustrated in Figure 65. In this chapter I trace the development of the tubes from their inception to the fully developed nozzle form and ask these questions. Why were the different types of tubes developed? Why did the form change over time? Why did the nozzle tube suddenly proliferate in North Africa when it did? What were the mechanisms by which it spread to other parts of the Mediterranean? What were the manifestations of the technique on the architecture that used it?

EARLY DEVELOPMENT OF VAULTING TUBES

The technique of building vaults using interlocking terracotta vessels is first found in the third century BCE in the North Baths at Morgantina in Sicily (Fig. 67).[5] The tubes were used in two barrel-vaulted rooms (5.0 and 5.5 m span), probably an *apodyterium* and *frigidarium*, and a domed room (5.75 m span) housing individual hip baths in the Greek tradition. The most recent excavator of this bath, S. Lucore, notes that two types of tubes have been found. Type 1 is in the form of a slightly curved water pipe and is heavier than Type 2 (15–17 cm diameter, 60–70 cm long), which is bullet shaped ending in a curving taper (Fig. 68). Type 2 seems to have been a lighter, improved version of Type 1.[6] Figure 67 illustrates both types of tubes; it also shows that the collar of one of the Type 1 water pipe tubes was chipped away to make it closer in form to the Type 2 bullet-shaped tube. Given that the majority of the tubes found are the lighter version (Type 2), there appears to have been some experimentation occurring on the site. Because of their large size and the need to be slightly curved to fit the arc of the vaults, the tubes had to be formed by hand (as opposed to being wheel-made) and were clearly made specifically for the context. Iron pins were occasionally used to connect and stabilize the tubes around openings in the vault.[7] Another early bath building at Syracuse (contrada Zappalà) (third century BCE) may have employed vaulting tubes, but the evidence is ambiguous. The excavator noted only fragments of "*stucco*" with imprints of "*fusti di arboscelli e forse anche di canne*" (trunks of saplings and perhaps also of canes), which could have been the imprints of tubes; if so he failed to recognize



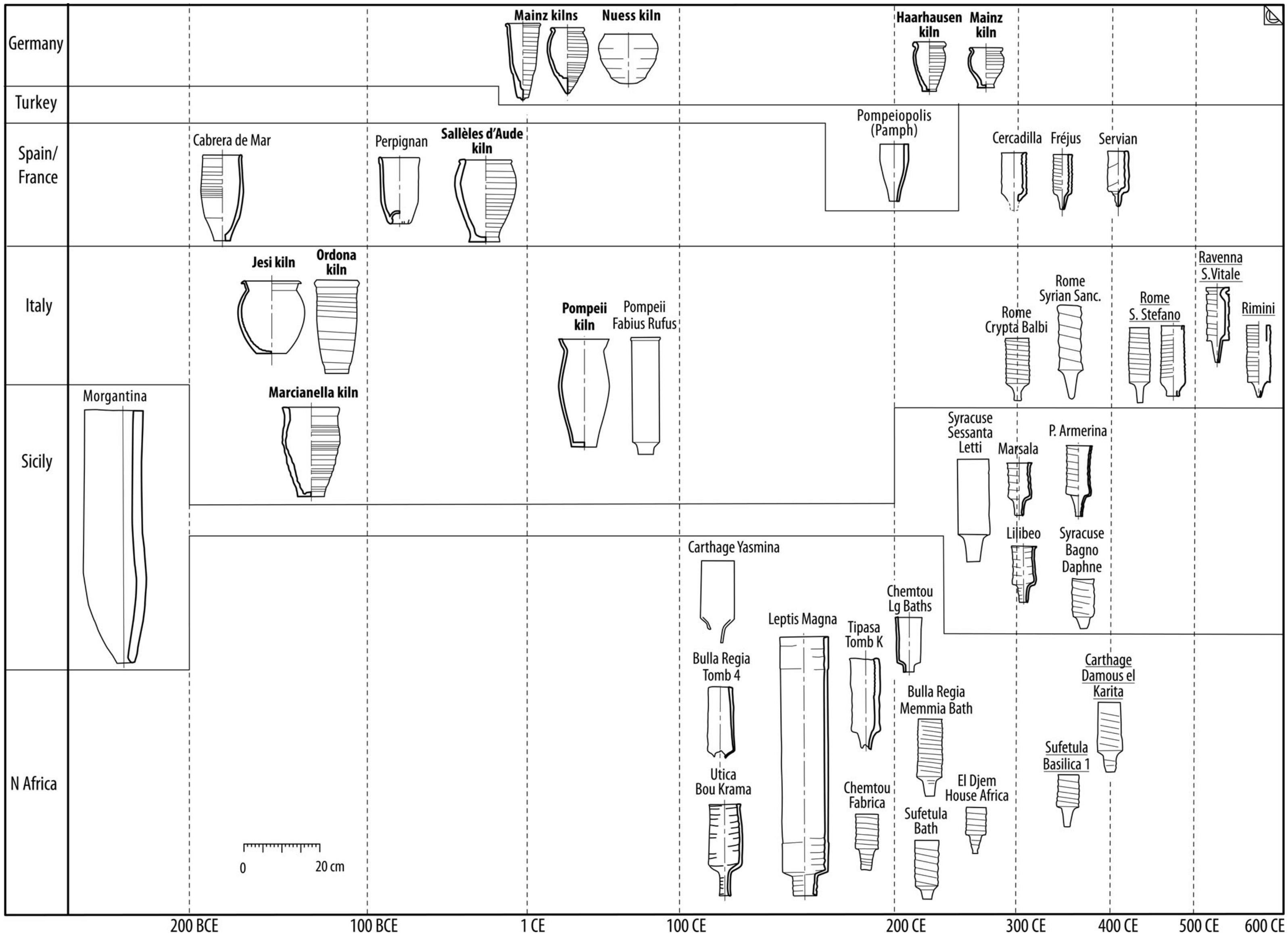
Land sites: **1** Vilar de Santos, **2** Mérida, **3** Cercadilla, **4** Granada, **5** *Complutum*, **6** Sagunt, **7** Tarragona, **8** Altafulla, **9** Cabrera de Mar, **10** Perpignan, **11** Montredon-des-Corbières, **12** Servian, **13** St.-Cyr-sur-Mer, **14** *Olbia*, **15** Trans-en-Provence, **16** Fréjus, **17** Limoges, **18** Caerleon, **19** Chester, **20** York, **21** Chesters, **22** Vercelli, **23** Milan, **24** Pavia, **25** Porto Torres, **26** Capo Lilibeo, **27** Mozia, **28** Favignana, **29** Alcamo Marina, **30** Giardinello, **31** Rapitalà, **32** Termini Imerese, **33** Vito Soldano, **34** Piazza Armerina, **35** Morgantina, **36** Catania, **37** Príolo, **38** Syracuse, **39** Curinga, **40** Sibari, **41** Valesio, **42** Vagni, **43** Pompeii, **44** Ostia, **45** Rome, **46** Perugia, **47** La Befa, **48** Florence, **49** Galeata, **50** Rimini/Forli/ Barisano, **51** Ravenna/Classe, **52** Comacchio, **53** Grado, **54** Orsera, **55** Pula, **56** Sibenik, **57** Sirmium, **58** Domavia, **59** Ravna, **60** Csáki-Gorbó, **61** *Pompeiopolis*, **62** Dura-Europus, **63** Pella, **64** Nazareth, **65** Bu Ngem, **66** Gasr Zerzi, **67** *Leptis Magna*, **68** Tripolis, **69** Sabratha, **70** Ras el Aïn Tlalet, **71** Djerba, **72** Djebel Tebaga, **73** La Skhira, **74** Mahrès, **75** Thina, **76** *Acholla*, **77** El Djem, **78** *Thapsus*, **79** *Leptiminus*, **80** Sousse, **81** Chott Mariem, **82** Sidi Khalifa, **83** Segermes, **84** Hammamet, **85** Nabeul, **86** Kelibia, **87** Kerkouane, **88** Utica, **89** *Belalis Maior*, **90** Sidi Ghrib, **91** Borj el Amri, **92** *Thuburbo Maius*, **93** Jebel Oust, **94** Oudna, **95** Bou Gornine, **96** Carthage, **97** Raqqada, **98** Sidi-Mohammed el-Guebiou, **99** *Mascliana*e, **100** Sidi Marzouk Tounsi, **101** Mactar, **102** Dougga, **103** Aïn Tounga, **104** Thibar, **105** Tabarka, **106** *Bulla Regia*, **107** Chemtou, **108** *Thuburnica*, **109** Ksiba, **110** Henchir Sidi Bou Gossa, **111** Doura Ethouar, **112** Le Kef, **113** Henchir Medeïna, **114** *Sufetula*, **115** *Cillium*, **116** *Thelepte*, **117** Henchir Safia, **118** Tébessa, **119** Haïdra, **120** Morsott, **121** *Madauros*, **122** *Tipasa Numidarum*, **123** Khamissa, **124** Announa, **125** *Hippo Regius*, **126** Oued Rhezel, **127** Oued Athménia, **128** Djemila, **129** Mons, **130** Sétif, **131** Lambèse, **132** Timgad, **133** *Aquae Flavianae*, **134** Négrine, **134** Tehouda, **136** Biskra, **137** *Saldae*, **138** Bordj el Bahri, **139** Bou Ismail, **140** *Tipasa*, **141** Cherchell, **142** *Tigava Castra*/*Municipium*, **143** Khamisti, **144** Kaoua, **145** Oued Rhiou, **146** Rélizane, **147** Bethiouia, **148** Ain Soltan, **149** Sidi Ali Ben Youb, **150** *Volubilis*, **151** *Banasa*; **Underwater finds:** **A** Escolletes B, **B** Capo Blanco, **C** Moro Boti A, **D** Mateille A, **E** Cap d'Agde, **F** Dramont E, **G** Port Vauban, **H** Punta Ala, **I** Punta del Fenaio, **J** Lavezzi VI (F), **K** Capo Carbonara B, **L** Acque Chiare, **M** Marsala harbor, **N** Levanzo I, **O** Himera, **P** Cefalù, **Q** Capo Graziano A, **R** Panarea, **S** Ognina A, **T** Plemmirio B, **U** Femmina Morta, **V** Pantelleria, **W** Caesarea Maritima; **Kiln pot sites:** **a** Xanten, **b** Neuss, **c** Cologne, **d** Soller, **e** Bonn, **f** Remagen, **g** Weissenthurm, **h** Speicher, **i** Haarhausen, **j** Mainz, **k** Seulberg/Heddernheim, **l** Hanau, **m** Rheinzabern, **n** Welzheim, **o** Altino, **p** Massa, **q** Ca Lo Spelli, **r** Marcianella, **s** Scoppieto, **t** Pompeii, **u** Ordona, **v** Jesi, **w** Santarcangelo/Riccione, **x** Forlì/Faenza, **y** Sallèles d'Aude

66. Distribution map of vaulting tubes and vaulting pots used for kiln roofs (WebCat. 5).

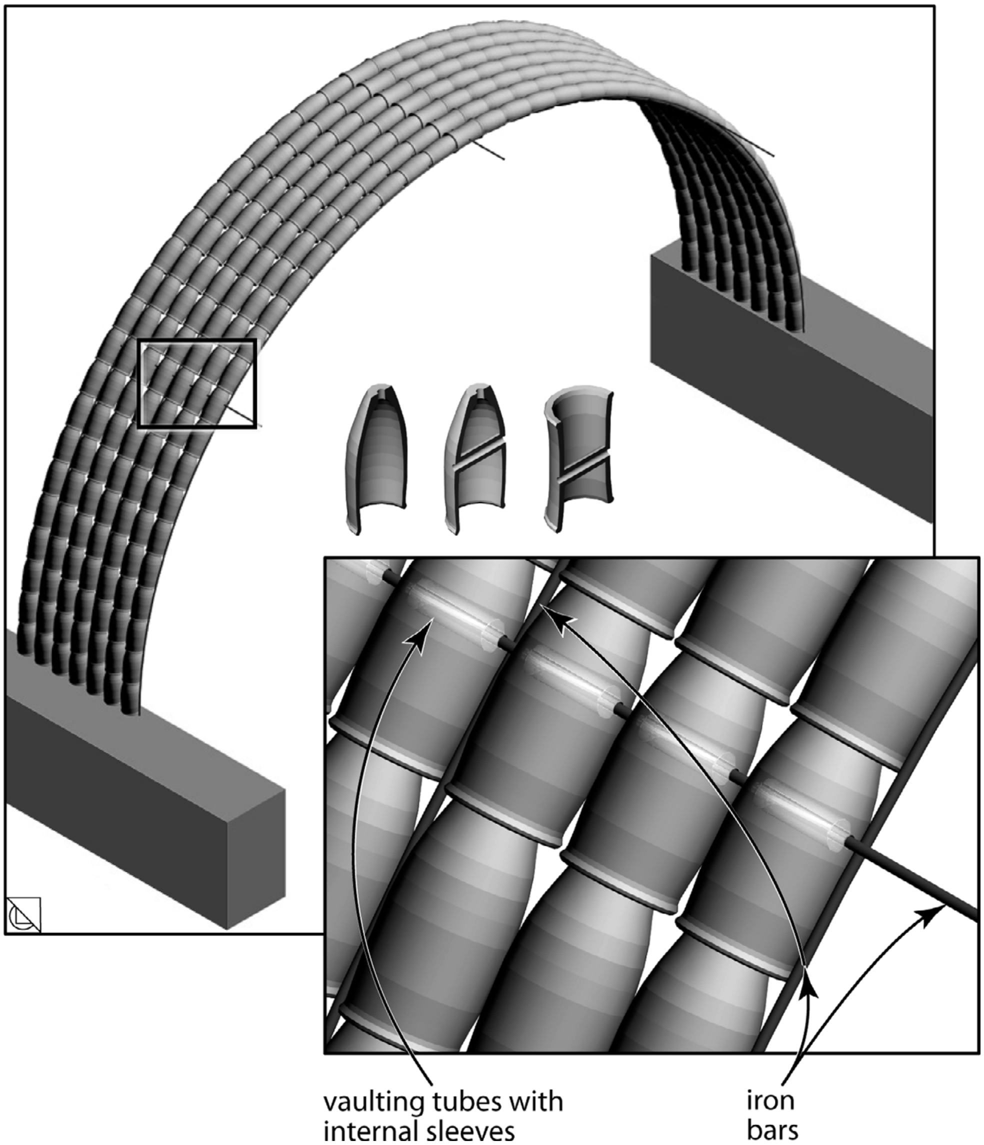
67. North Baths at Morgantina (mid-third century BCE). View of fallen vaulting tubes in the immersion bath of the *caldarium* showing a water pipe (Type 1) tube in the foreground with another next to it with the nozzle chiseled off to approximate a bullet-shaped tube (Type 2). In the background, a Type 2 bullet-shaped tube is visible (photo: Sandra Lucore).

the discovery and therefore gave no indication of their size or form.[8]

Two other pre-imperial examples of vaulting tubes are known. A modified version of the technique at Morgantina has been found in a mid-second-century BCE bath at Cabrera de Mar near Barcelona where tubes from the fallen vault were excavated in situ. The baths are located in a partially excavated settlement at Ca l'Arnau, less than a kilometer from the indigenous *oppidum* at Burriac. It appears to have been inhabited from about the mid-second century to the early first century BCE. The bath is an early Roman type with an *apodyterium*, a *tepidarium*, and a *caldarium* containing a hot pool. Few details have been published, but the excavator notes that the tubes were used in a barrel vault over the *caldarium* (5 m span) and a dome (?) over the *tepidarium* (3 m square).[9] These tubes are much smaller (11 cm diameter, 22 cm long) than the Morgantina ones, and they are wheel-made, but they take a similar bullet shape so that each rounded end could be inserted into the open end of the adjacent one (Fig. 69). Three different types of units are cited in the excavation report: bullet-shaped tubes, bullet-shaped tubes with a transverse internal sleeve to house



68. Chart showing the development of vaulting tubes and pots over time and by region. Bold text indicates vaulting pots for kilns. Underlined text indicates a Christian context.



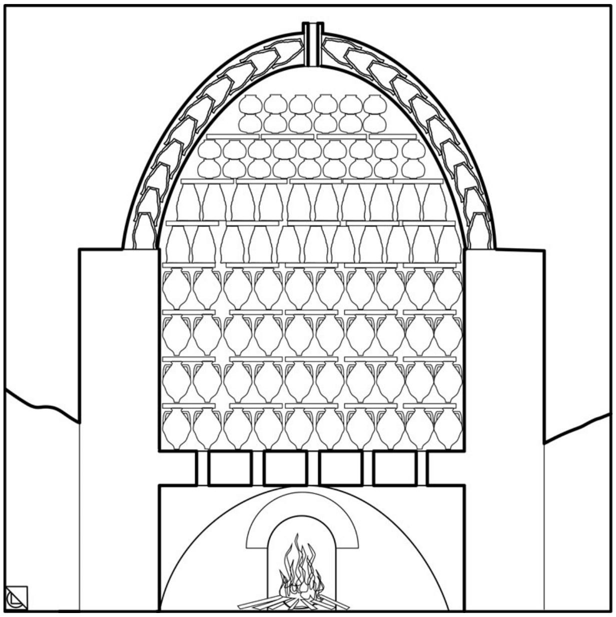
69. Bath at Cabrera de Mar, Spain (mid-second century BCE). Author's reconstruction of the system of vaulting using vaulting tubes and iron bars (based on description in Martín 2000).

iron connectors, and a cylindrical collar with a similar internal sleeve. The cylindrical collar was used to connect the end of the tubes from each side where they met at the crown of the barrel vault. The iron bar ran through the hollow sleeves to connect the crown cylinders. At some point midway along the haunch a similar type bar ran through the sleeves in the bullet-shaped tubes. The tubes were connected with lime mortar and covered with the same mortar on both the extrados (5 cm) and intrados (3 cm).[10] The intricate fabrication of these tubes suggests that they, like those at Morgantina, were made for a particular context and not mass produced. Another type of tube vault has also been found at a mid-first-century BCE bath at Perpignan (ancient Ruscino), France about 175 km up the coast from Cabrera de Mar. It is not well documented, but the form of the vaulting elements has been recorded. They are roughly similar to those at Cabrera de Mar, but are slightly smaller, and they have indentations at the small end rather than a hole (Fig. 68).[11] The tubes at all three sites occur in bath buildings at a time before concrete vaulting was developed in these regions. As suggested by Wilson, the impetus to develop such a vault was probably the desire to have a safer and longer lasting structure than a wooden one, which would have been susceptible to fire and rot.[12]

Various proposals have been made regarding the influences that stimulated the invention of these earliest tube vaults. As we saw earlier, in Figure 67, the neck of one of the heavier water-pipe type tubes at Morgantina was chipped away to make it narrower, and Lucore reasonably proposes that the builders began by adopting an existing technology (the water-pipe) and then began modifying it until they came up with the bullet-shaped tube.[13] Two later examples of water-pipe forms used at Pompeii and Leptis Magna support this idea (see the later discussion). Both Storz and Wilson suggest that pots used to build kiln roofs could have been the inspiration for the tubes,[14] but thus far the earliest evidence from kilns comes from the mid-second century BCE at Jesi, Italy.[15] Other examples dating to the second half of the second century or early first century BCE have been found at Marcianella, Ordona, Massa and Ca Lo Spelli (Fig. 68).[16] All are significantly later than the tubes at Morgantina, where N. Cuomo di Caprio notes that no kilns with vaulting pots have been found.[17] Nevertheless, that the potter was involved in the invention seems certain. Careful examination of the pots suggests that, with the exception of the example at Jesi, potters were not using wasters (as was once thought), but instead were creating purpose-made pots for kiln construction.[18] The pots have often been found with the remains of binding mortar consisting of a mud slurry, which was fired on the first use of the kiln. In addition to providing an easy method of building the kiln roofs, the pots would have also provided additional thermal insulation.

Since the studies of Storz and Wilson came out, numerous vaulting pots from kilns have come to light that provide a more comprehensive view of the development of this type of kiln construction (WebCat. 5-C). Current evidence indicates that it began during the second century BCE in Italy and later was common from the Augustan period through the third century CE. The vaulting pots have been found in kiln sites in southern France, in the Po Valley, in Pompeii, and in Germany especially along the Rhine (Figs. 67, 68).[19] Earlier suggestions that the vaulting tubes were influenced by the Punic use of reed mats are less convincing.[20]

Experimentation can be detected in the period between the occurrence of the first vaulting tubes at Morgantina in the third century BCE and of the smaller nozzle tubes that appear in North Africa in the second century CE.[21] The use of iron connectors for the tubes at Morgantina and Cabrera de Mar, mentioned earlier, was not repeated in later examples. The vaulting tubes in the first-century BCE bath at Perpignan are instructive because, given the closed ends, they seem to be more like the vaulting pots in the kiln roofs (Figs. 68, 70). Pompeii also provides some insight into the development of the technique because it has examples of vaulting pots in kiln roofs as well as water-pipes used as vaulting tubes in the vault of a house. The vaulting pots were found in two kilns, one outside the Herculaneum gate and another on Via Nocera (1.20.3) (Fig. 68).[22] The architectural example is in a small vault in a back corridor of the House of M. Fabius Rufus (7.occ.17–22). The tubes (33 cm long) were in the form of water-pipes, and the variation in the diameters of 6–8 cm suggests that they were not purpose made for the vault. In addition, they were used in a very unusual manner – they were found adhered to the intrados of the vault by

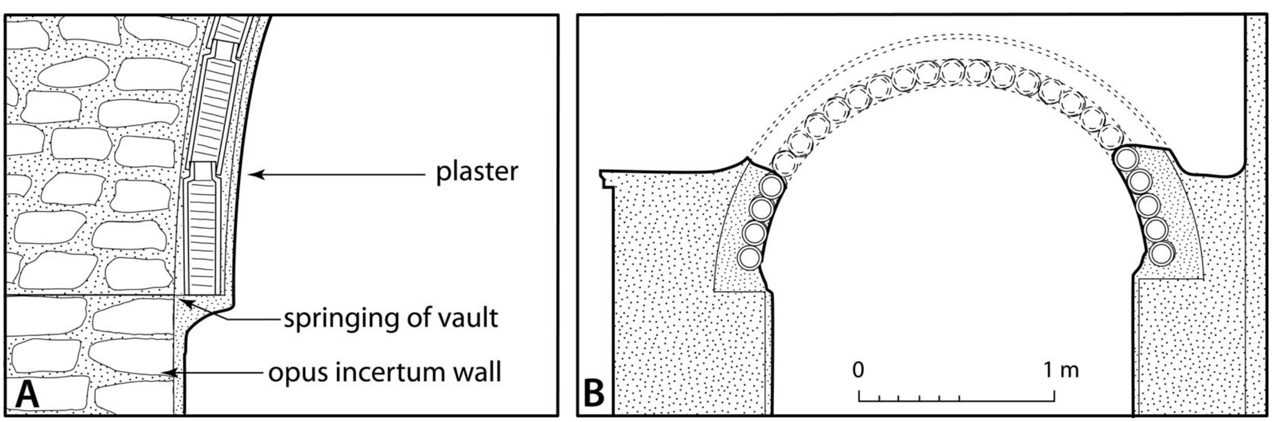


70. Reconstruction of a generic loaded kiln employing vaulting pots for the roof.

means of lime mortar (not gypsum), but they projected from the wall rather than being supported by it (Fig. 71A). P. Scurati-Manzoni suggests that they were placed over a lightweight wooden centering to make it more rigid. After the centering was removed, the tubes remained adhered to the intrados and were plastered over. He also notes that a cistern at Via di Castricio, on the east side of town, was found with tubes (form unknown) along the intrados but was not excavated because of its precarious condition.[23] The existence of the vaulting pots for kiln roofs and water-pipes along the intrados of vaults at Pompeii suggests that some cross-fertilization was occurring within the city during the mid-first century CE. Another unusual example of water-pipe type tubes occurs at a mid-second-century CE cistern at Leptis Magna where long tubes (79 cm) were placed parallel to the axis of the barrel vault instead of forming arches of interlocking small tubes (Figs. 68, 71B).[24] These peculiar uses of water-pipes suggest a period of experimentation that continued outside Africa Proconsularis well into the second century.

INTRODUCTION OF VAULTING TUBES WITH NOZZLES

The vaulting tubes that eventually became ubiquitous in North Africa are different in form from the earlier bullet-shaped types and the kiln pots. The fully developed form had a distinct break in the profile where

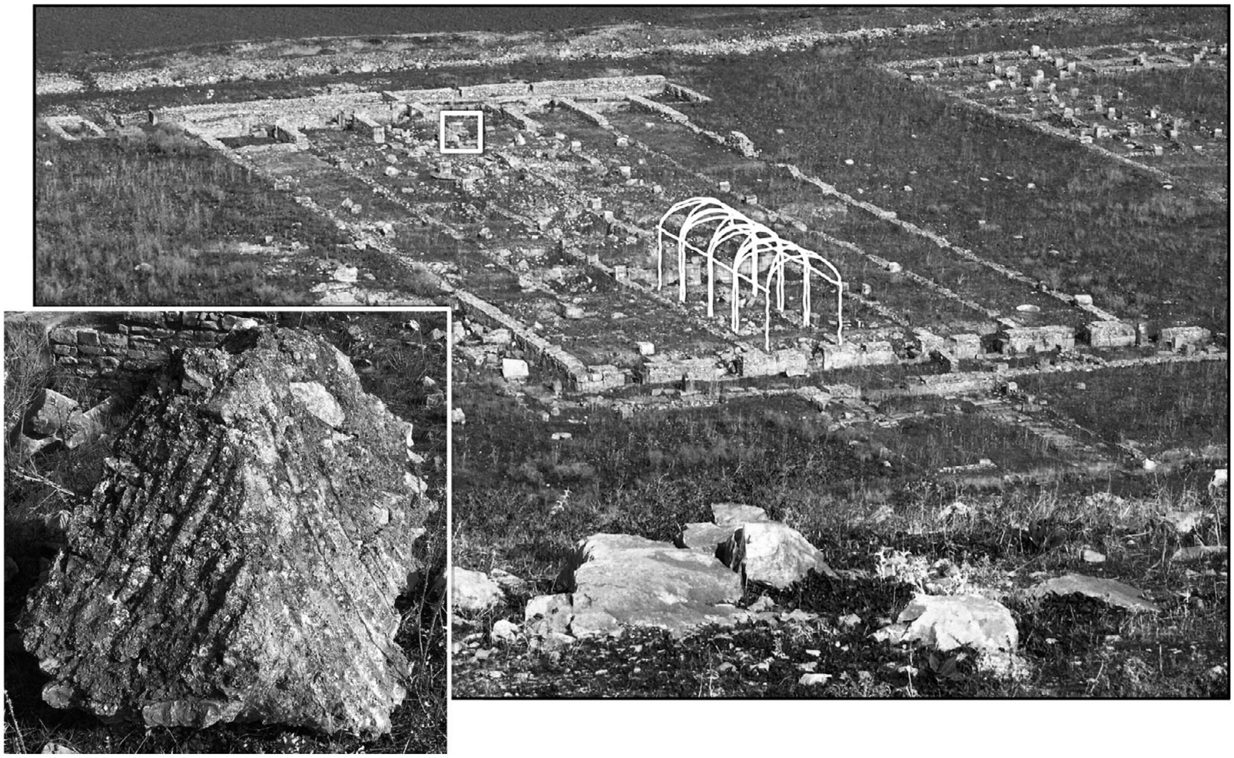


71. Examples of the use of water-pipe type tubes. A: House of Fabius Rufus, Pompeii (7.occ.17–22). Section drawing of corridor with tubes on the vault. Note that the tubes project out from and are not supported by the wall (after Scurati-Manzoni 1997: fig. 5). B: Section drawing of vault of the cistern of the Nymphaeum of the Chalcidium at Leptis Magna (second century CE) in which the tubes were placed parallel to the axis of the vault and thus not used in a structural manner (after Tomasello 2005b: fig. 1).

one end was formed as a concave nozzle that would fit into the open end of the next tube (Fig. 65). The tubes averaged around 6 cm in diameter, though diameters varied from 5–10 cm. The smaller size and the nozzle were critical developments because they enhanced the usability of the tube. Its reduced size and weight allowed a single workman on scaffolding to lift and put it into place easily. The nozzle also allowed greater play between the elements than did the bullet form, so a single-sized tube could create a great range of vault sizes: a one-size-fits-all solution. However, the tubes were not absolutely regular, and the length could vary greatly from about 6 cm to 35 cm, the typical range being 12–20 cm. In his analysis of the tubes, Storz finds that the length could even vary within a single vault and that there was no great correlation between vault span and tube length.[25] More critical was a consistent diameter so that the tubes in any one vault could fit together. The nozzle tubes were held together with quick-drying gypsum mortar (basically Plaster of Paris), so very large spans could be built without centering by essentially "gluing" one tube to the next, in much the same way pitched brick was laid. The tubes also display distinct grooves spiraling the length of the cylinder. In most cases these are finger grooves resulting from the process of the potter drawing the cylinder up on the wheel as it turned, but some tubes also display ridges created with a tool. Storz notes that some ridges even appear to have been applied to the exterior of the tube after it had dried to a leather hard state.[26] Such a practice indicates that the corrugation was considered an essential aspect of the tube, presumably because it provided better purchase for the mortar.

The earliest examples of the nozzle tube appear in North Africa during the second century CE in tomb contexts.[27] A. Lézine cites an example (9.3 cm dia., 24.3 cm long) from Utica at the Bou Krama necropolis, which he notes did not continue past the early second century CE. Its form is somewhat larger than the typical ones and has an unusually shaped nozzle (Fig. 68). The context in which the tube was found is not explained.[28] Three other examples come from funerary contexts at Bulla Regia, Tipasa, and Carthage. At Bulla Regia vaulting tubes were used to form a libation pipe in a mid-second-century tomb. At another mid-second-century tomb in Tipasa, Algeria, the tubes were found as part of the fallen vault.[29] The third example comes from a second-century (?) mausoleum at the Yasmina cemetery (#3006) at Carthage where some of the tubes are still in situ.[30] All of the tubes from these examples are somewhat larger (8–10 cm) than the ones that became more standard during the third century, but the form is basically similar (Fig. 68).

The archetypal nozzle tube with a diameter of 6–7 cm, pronounced exterior corrugations, and a clearly defined nozzle appears some time in the second half of the second century CE. At Chemtou (ancient Simitthus), tubes (6 cm dia.) were used for the cross vaults (5 m span) covering the central aisle of the six-aisled structure, known as the *fabrica*, which housed activities associated with the adjacent giallo antico marble quarries (Fig. 72). This building has a *terminus post quem* provided by a piece of marble in the foundation bearing a quarry inscription with a consular date of 154 CE. Based on the excavated coins and fine ware (African Red Slip), an original construction date of around 170 CE has been proposed;[31] however, as Storz notes, there is a possibility that the vaults could date from the slightly later phase in the early Severan period when other modifications to the complex took place after the aqueduct was built.[32] Another potential Antonine example comes from Dougga (ancient Thugga) in a series of small (1.0 × 1.5 m) cross vaults supporting the stage of the theater. An inscription dated to 168/9 CE names the donor for the construction of the theater and its scene-building as P. Marcius Quadrata. C. Poinssot considered the existing remains of the stage to be part

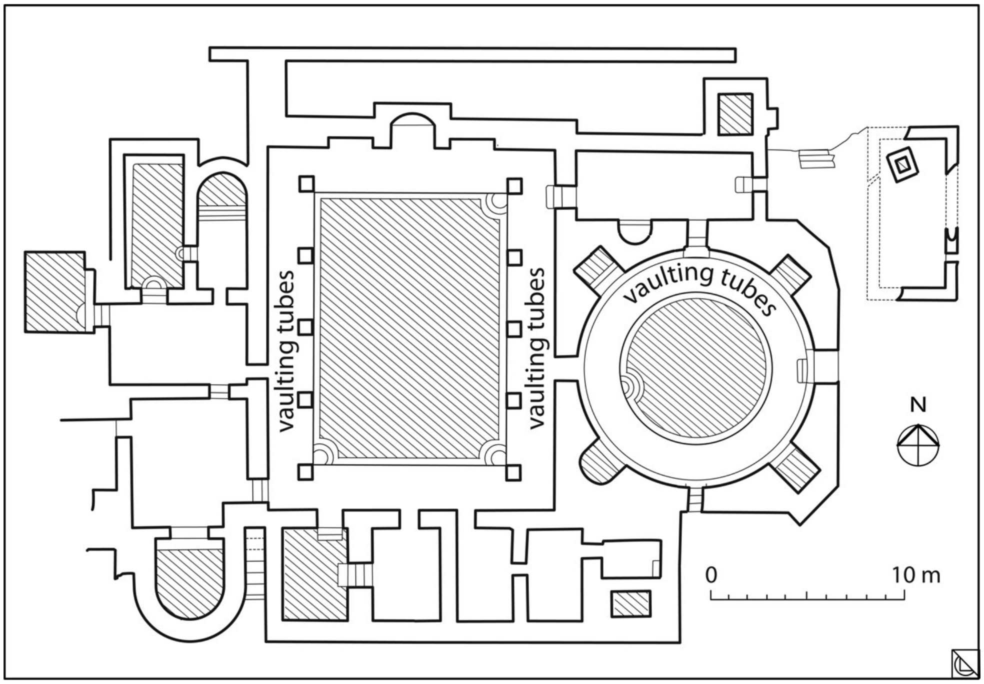


72. *Fabrica* at Chemtou, Tunisia. Inset shows fallen cross vault from central aisle with impressions of tubes along the intrados. Vault configuration is sketched in.

of the original, whereas Lézine argued that it and the mosaic that it supported should be dated later, citing other (unpublished) examples of late antique renovations to stages, including one at Bulla Regia.[33] The small scale of the vaults and difficulty of building them so close to the ground (0.80 m) would make this an appropriate context for testing the benefits of a technique that allowed for the elimination of centering, but without further dating criteria its date remains ambiguous. Certainly by the early Severan period, the small nozzle tubes were common in North Africa, and the technique had even been exported to other parts of the empire.

ROLE OF THE MILITARY IN THE DIFFUSION OUTSIDE NORTH AFRICA

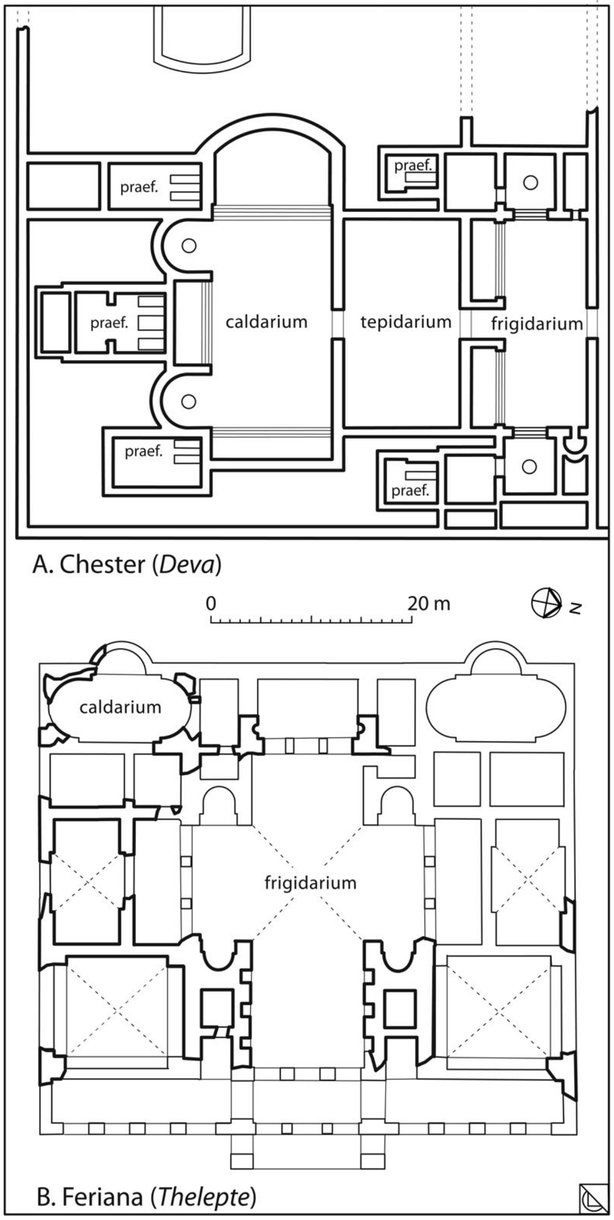
Many of the early Severan examples both within North Africa and elsewhere are associated with military structures. As discussed, the earliest development of the nozzle tubes appears in civilian funerary contexts, but the early diffusion of the technique outside of Africa Proconsularis is found exclusively in military contexts. By the second century CE, the main legionary base in North Africa was located at Lambaesis in Algeria – the Legio III Augusta was stationed there – and various inscriptions indicate that detachments of soldiers were often sent out to aid in construction projects.[34] The example from the *fabrica* at Chemtou, mentioned earlier, is not strictly a permanent military site (as was originally proposed),[35] but because it was the center of imperial quarrying activity, the work was likely overseen by military personnel whose presence is attested there in inscriptions.[36] More definitive military activity is recorded elsewhere. An inscription dated to 201/2 CE records that the men of Legio III were active at a military



73. Plan of bath at Aquae Flavianae, Algeria (208 CE). Hatched areas indicate pools. Fallen vaulting tubes were found in the circular room and along the aisles of the main rectangular pool (plan based on Gsell 1901, 1: 238 fig. 72).

outpost at Bu Ngem in Libya where they built a bath employing vaulting tubes in a series of average-sized vaults (5.25 m max. span).[37] A few years later but closer to home, inscriptions dated to 208 CE record the activities of a *vexillation* (legion not indicated but presumably Legio III) that rebuilt a Vespasianic bath at the hot springs of Aquae Flavianae, about 90 km east of the Lambaesis along the main road to Carthage.[38] The two main rooms of the bath were both found with vaulting tubes on the floor, though the vaults no longer remain. The rectangular room had (cross?) vaulted porticoes (c. 1.7 m span) supported on piers on the two long sides with an open-air pool in the center. The 12 m span of the circular room would have been covered by a dome (Fig. 73).[39] The technique represents an advanced use of the technique because the dome is among the largest known from North Africa.

Outside North Africa the initial uses of the nozzle tubes can all be associated with a military presence: baths at the three main legionary fortresses in Britain (Chester (ancient Deva), Caerleon (ancient Isca Augusta), and York (ancient Eboracum)), at a small fort at Chesters (ancient Cilurnium) on Hadrian's Wall, and at bath F3 at Dura-Europus in Syria. The best documented use is from the 12 m *tepidarium* vault (form unknown) of the legionary fortress baths at Chester, which was excavated in 1964 (Fig. 74A). A layer of soft earth had accumulated before the vault fell and served to cushion the blow so that when the vault was excavated the stratigraphy was clear: a layer of plaster lining the intrados, two layers of vaulting tubes in five rows joined with plaster (gypsum mortar), a 30 cm thick layer of "decayed concrete," and finally a layer of roof tiles.[40] Stray finds of tubes were also excavated in the *caldarium*, suggesting that the entire complex employed the technique. The vaults most likely belong to the Severan work that is recorded elsewhere in the fortress. Stray vaulting tubes were found at several other

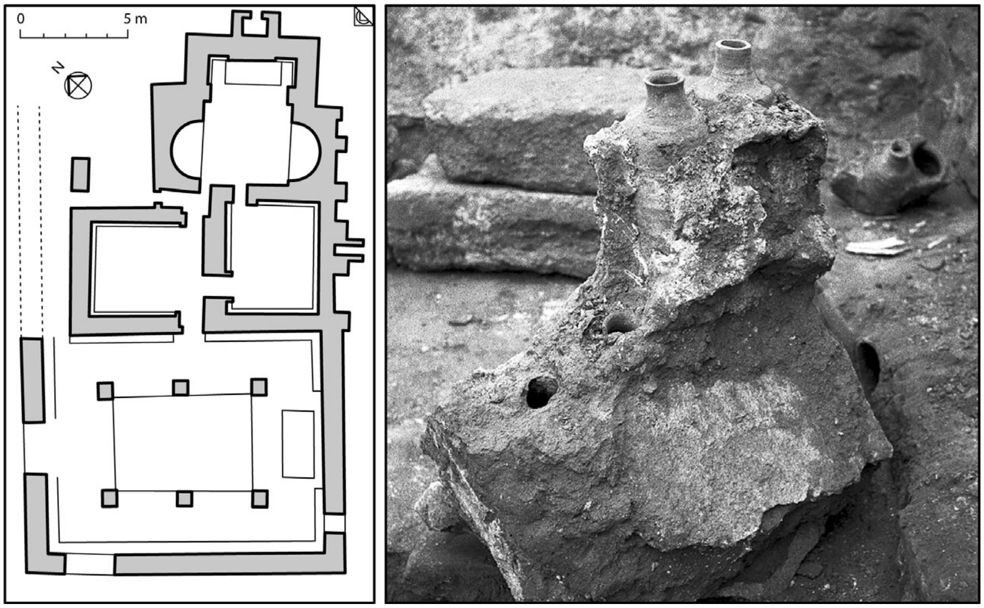


74. Comparison of plans of similar sized baths employing tube vaults. A: Legionary Baths at Chester, England (phase 2: early third century CE) (reconstructed plan based on Mason 2005: fig. III 51). B: Baths at Thelepte, Tunisia (third century CE?) (reconstructed plan based on Krencker et al. 1929: Abb. 226 and Saladin 1887: fig. 206).

military sites: another bath at Chester in the so-called elliptical building (Severan),[41] the Legionary Baths and the Castle Baths at Caerleon, and the legionary baths at York.[42] Others have also been found at the military fort at Chesters on Hadrian's Wall, though the findspots are not recorded.[43] No examples from civilian sites are known in Britain. D. Mason suggested the likelihood that the legionary baths in Britain all underwent refurbishment under the Severans, possibly with the intervention of an architect from North Africa.[44]

The most exhaustive study of the evidence from terracotta production for military connections between Britain and North Africa is V. Swan's discussion of the appearance of distinctive North African pottery forms produced in military contexts in Britain.[45] Her focus is on pottery evidence from York, whereas her discussion of inscriptional evidence for North African soldiers in Britain includes Caerleon, Chester, and forts on Hadrian's Wall. Much of the inscriptional and pottery evidence is dated to the late second and early third centuries when the vaulting tubes are likely dated. As Mason suggested, a North African military architect for the design of the baths is possible, but even more important in the choice to use the tubes for such large structures was the availability of potters to produce them. If Swan is correct in identifying the presence in Britain of North African potters for the distinctive types of North African cook ware that appeared in military contexts, the use of the tubes in the same contexts may be as much a reflection of the presence of North African pottery specialists as of a North African architect.

One further example of a military connection with the vaulting tubes occurs at bath F3 at Dura-Europus, which was originally dated by the excavator, F. E. Brown, to the Parthian period in the mid-first century CE; however, the recent consensus is that a late second-century date is more likely.[46] N. Pollard has investigated the issue in detail by reviewing the archival material and found that even Brown had some doubts on the early date at the time. The baths have a definite *terminus ante quem* established by the construction of an amphitheater on the site



75. Plan of bath F3 at Dura-Europus, Syria (left) with photo (right) of fallen tube vault from portico (photo: Yale University Art Gallery, Dura-Europos Collection).

in 216 CE,[47] which led Brown to suggest a much earlier date for their original construction. However, Pollard argues that these baths were built for the military units stationed there by the late second century. He notes the presence of members of Legio III Augusta in Syria and the East throughout the second century, who could have introduced the idea of the vaulting tubes to Dura.[48] The preserved fragment of the vault found in the porticoed *frigidarium* at bath F3 are interpreted by Brown as forming the intrados of one of the arches connecting the portico piers (c. 2.5 m span).[49] The excavation photo shows the tubes embedded into the mortar of the arch (Fig. 75), which is unusual because they are usually used to support the concrete and form a separate layer. The nature of the mortar is not noted (i.e., gypsum or lime), but much of the bath was built with gypsum blocks so one wonders if the tubes in the photo could have been embedded in gypsum mortar, given its prevalent use at the site. Brown concluded that the span of the portico (c. 2.0 m) and the size of the piers preclude that the tubes formed the centering for a mortared rubble "tunnel vault" over the portico, so he restored it with a wooden roof structure.[50] However, as we just saw at Aquae Flavianae, this is precisely the structural situation in which the tubes were employed there, and as we see later, the tubes were used for a 2.5 m vaulted portico at the House of the Hunt in Bulla Regia. Thus a portico covered by a tube vault should not be ruled out at Dura (see Chapter 8).

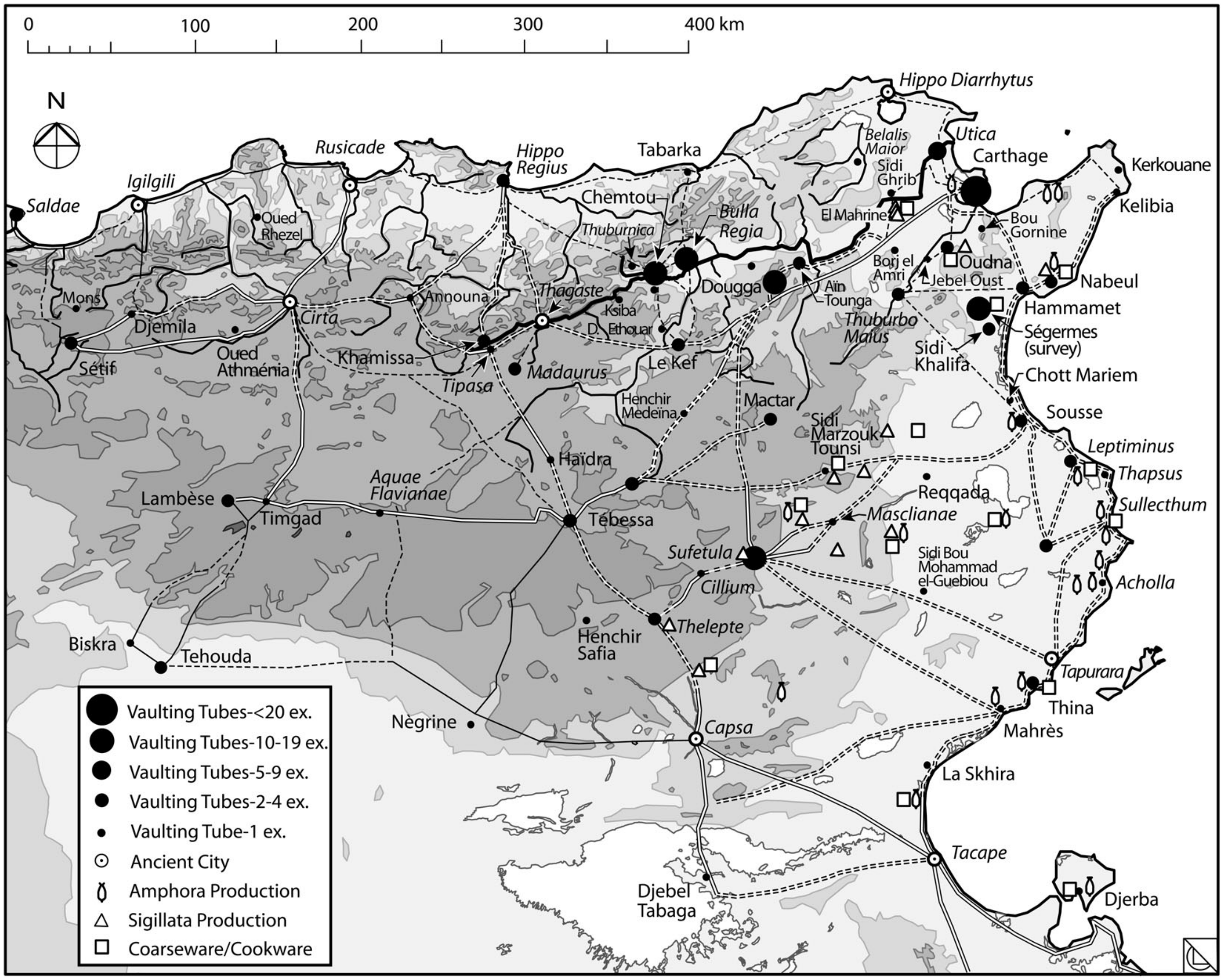
The presence of the vaulting tubes in the early examples of tomb architecture in Africa Proconsularis suggests that the military was not instrumental in the invention of the nozzle tube, but that military builders adopted it quickly and were apparently a major means of its initial diffusion in the early Severan period. Vaulting tubes outside North Africa that clearly do not relate to the military are mainly found in the western empire in areas that traded with North Africa, such as Sicily, southern Italy, and the southern coasts of Spain and France (Fig. 66). Sporadic examples occur in Bosnia Herzogovenia, Serbia, and Romania, but these are not well documented, so the dates and contexts are difficult to assess.[51] Another outlier, recently published, was found in a second/third-century CE villa bath from Pompeiopolis in Paphlagonia in northern Turkey. These tubes, anomalous in Asia Minor, have an unusual cone shape very similar to ones found at a bath at Csáki-Gorbó, Hungary.[52] The military was thus not the exclusive means of diffusion outside North Africa, but it was a major agent in the early phase of technology transfer.

THE NORTH AFRICAN ECONOMY

The invention of vaulting tubes occurred more than four centuries before nozzle tubes began to proliferate in North Africa. If vaulting tubes (and pots) were known and used in various forms for so long, what caused them suddenly to become ubiquitous in North Africa toward the end of the second century CE? The answer probably lies in the complex economic interactions that brought North Africa to the fore as a major exporter of both food and terracotta to Rome and other parts of the Mediterranean. More than forty years ago, A. Carandini proposed the idea of a connection between the growth of ceramic production and olive cultivation in Africa Proconsularis.[53] He was not interested in vaulting tubes at the time, but the ideas about interconnected commerce that he raised are relevant to the present investigation, especially in light of more recent evidence.[54]

North Africa's increasing importance during the second century both as a producer of grain for Rome as part of the *annona* and as a source of fine ware and lamps is well recognized. The imperial effort to increase the production of wine and olive oil is documented in a series of inscriptions found in the Medjerda river valley near Dougga starting in the early second century. A Trajanic inscription found at Henchir-Mettich (CE 116–117) authorizes sharecroppers (*coloni*) working on imperial estates to take over unused lands, noting the amount of each crop that they were obliged to pay in rent each season. Of particular interest is the clause that released the sharecropper from the obligation of rent in kind for five years after planting vines or fig trees and for ten years after planting olive trees. It also ensured that his heirs could continue to use the land after his death.[55] Two later inscriptions found in the same area at Aïn-el Djemala (117–138 CE) and Aïn Wassel (198–209 CE) refer to the *lex Hadriana de rudibus agris*, a law under Hadrian that set forth regulations for taking over neglected lands, particularly in marshes and forests, in order to set up olive orchards and vineyards.[56] Unlike grain, which produces the year it is planted, these crops require time to mature, so the laws provided an incentive for sharecroppers to make a long-term investment in olives and vines and to clear and maintain marginal lands. The effects can be seen in the arid areas of the inland steppes around Cillium (modern Kasserine), between Thelepte (modern Feriana) and Sufetula (modern Sbeitla), where surveys recording villas, irrigation, and oil presses indicate that by the third century the area was extensively developed for olive cultivation.[57]

The economic effect on the people in these regions is demonstrated by two inscriptions recording the agricultural success of wealthy men at Cillium and Mactar. The first is on an impressive mausoleum sitting along the major road into Cillum, which celebrates the accomplishments of the Flavius family with long poems inscribed on its walls. One of them notes that T. Flavius Secundus, who died in the second half of the second century, had introduced irrigation and vineyards to the area and with them the pleasures of Bacchus.[58] The second is the well-known inscription of the Harvester of Mactar (third century CE) that describes the life of a lowly itinerant field worker who managed to rise to become a prominent member of his town through the grain trade.[59] As pointed out by F. De Romanis the increased production in these inland areas also required the building of roads to



76. Map of Africa Proconsularis showing the distribution of vaulting tubes in relation to roads and terracotta workshops.

connect them to the ports for exportation. The roads were built with imperial investment as indicated by various Hadrianic milestone inscriptions (Fig. 76).[60] They also provided new opportunities for the movement of other types of products.[61]

With increased exportation of liquid foodstuffs came an increased demand for terracotta amphoras in which to ship them, which in turn affected other classes of pottery production, including the vaulting tubes. The *annona* was originally the system set up by Augustus to provide grain for the city of Rome, but an inscription from Seville suggests that by the 160s olive oil had been added to the system.[62] During the second half of the second century the appearance of the widely distributed African amphoras is an indication of the increased levels of olive oil, fish products, and wine being produced in Africa Proconsularis during this period.[63] Accompanying the increased production of amphoras was a change in the scale of fine ware production, with African Red Slip (ARS) A, which had been manufactured since Flavian times, beginning to dominate the Mediterranean market around 160–180 CE.[64] Though the workshops where it was produced have not been located, archaeometric analysis indicates that they were in the north of Africa Proconsularis, likely somewhere around Carthage.[65] By the beginning of the third century new workshops producing ARS C appeared in central Tunisia, thus indicating an expansion of the industry toward the south.[66] The spread of the vaulting tubes from Chemtou and Bulla Regia during the second century southward to Thelepte and Sufetula during the third century is another indication of the expansion of ceramic production.

Increased agricultural production moving ever farther inland led to more developed infrastructure for producing terracotta items on a much larger scale.[67] This infrastructure included the road networks as well as production equipment, such as turning wheels, drying areas, skilled labor for producing different types of vessels, and kilns for firing. The vaulting tubes were likely made reasonably close to the site where they were to be used because great quantities were required for even a small vault. For example, a small vault (1.75 m × 1.85 m) reconstructed at Bulla Regia required 944 tubes.[68] The largest surviving dome of vaulting tubes at San Vitale in Ravenna (15.6 m dia.) employs around 66,000 tubes.[69] Mason estimated that the Legionary Baths at Chester in England would have required more than 219,000 vaulting tubes.[70] The bath building at Thelepte (Fig. 74B) is similar in size to the one at Chester, so one can imagine that the number of tubes required for it would have been of a similar order of magnitude. The sheer number required for such large structures would have required efficient production processes. The finger grooves on the tubes show that they were thrown on a wheel, which would have allowed them to be created very quickly. One experimental study has shown that a single tube can be thrown in less than one minute.[71]

The known ceramic production sites all included some types of vessels turned on a wheel – amphoras, coarse ware, or fine ware[72] – so the tubes could be made with the available manpower and equipment at most facilities. Unfortunately, vaulting tubes can rarely be associated with particular workshops. But two documented examples are known: one at Meninx (modern Djerba) in an area of kilns that were producing coarse wares and Keay 25 amphoras (for wine or olives?)[73] and another at Uthina (modern Oudna) associated with fifth- to seventh-century kilns producing fine ware, lamps, and coarse ware.[74] Given the numbers needed, the vaulting tubes would have required a great deal of kiln space, which is one reason that a highly developed industry was necessary to make them a reasonable choice. As noted earlier, the inland workshops tended to specialize in fine ware, and one aspect of the African sigillata production is that the wares were fired in normal kilns and protected in saggars, in contrast to the method in Gaul, which employed specially made kilns with terracotta pipes containing the gases. The use of normal kilns meant that the same kiln could be used for both fine ware and coarse ware, which in turn would have allowed for the flexibility to produce the vaulting tubes in the same workshops as the fine ware.[75] Indeed coarse ware has been found to be a small proportion of the output of fine ware workshops.[76]

M. Mackensen's analysis of the graffiti on saggars from El Mahrine in central Tunisia, which name different workshop owners, suggests that communal kilns were used, which were presumably operated by specially trained firing masters.[77] This organizational model would have lent itself to the firing of special commissions for large batches of vaulting tubes and also for itinerant specialists who could have traveled to building sites and hired local facilities (see Chapter 6 for details on this production mode attested in Britain). Taking as a model the second- to third-century CE Kiln A at Leptiminus (4.9 m int. dia.), which fired Africana I and II amphoras,[78] we can calculate the number of tubes that could have been fired in a large kiln. With a minimum assumed height of

1 m, this kiln could hold 20,000 tubes (6.5 cm diameter each with a stackable height of 15 cm), which would require around ten firings for a project the size of the Thelepte baths; fewer firings would be needed with a taller kiln. As a comparison, a smaller kiln (1.7 m int. dia.) with an assumed height equal to its diameter could hold about 4,000 tubes, which would require fifty-five firings for the same project. Clearly the scale of the available firing facilities would have been a major factor in the decision to use the tubes.

AN EXPORT COMMODITY?

Vaulting tubes have been found in more than twenty-five shipwrecks, most of which were in the western Mediterranean off the coasts of Italy, France, and Spain (Fig. 66, WebCat. 5-B).[79] Very often they are found together with Tunisian amphoras or fine ware, which has raised the question of whether they were an export item.[80] In the excavation reports, the number of tubes reported is rarely more than about thirty,[81] though M. Bound notes that the wreck at Punta Fenaio (third/fourth century CE) contained "a large number" mixed with the cargo of amphoras. The ones he examined from this site and from Marsala exhibited the typical creamy surface often found on North African pottery, implying that they were made there.[82] A recently excavated shipwreck (mid to late fourth century CE) off the coast of Sicily near the island of Levanzo has revealed an intriguing find of more than a hundred vaulting tubes located together within a rectangular area of 1.5 × 1.8 m. The excavators report that no mortar was found attached to the tubes (though gypsum mortar would have dissolved), and they argue that the tubes must have been cargo, rather than part of the ship's structure.[83] If so, one is left wondering what value a hundred tubes, or even twice that many, could have had in the larger scheme of a building project. As we saw earlier, even a small vault would employ close to a thousand tubes, so any evidence for significant trade would require numbers into at least the four digits. In general, the tubes would not have been an economical export item in small numbers because they are only valuable when acquired in quantity, unlike fine ware and lamps that have individual worth. Unlike bricks, which could be densely packed, they would not have made effective ballast, given that they were hollow. The number of tubes found on shipwrecks is usually so small that the explanation for their presence is more likely that they were used as cargo filler, as bilge pipes, or as fireproof material to build small structures on the ships themselves, rather than as a primary export commodity.[84]

PURPOSE OF THE NOZZLE TUBES

Various factors have been suggested for why vaulting tubes became so popular. Given that the early vaulting tubes at Morgantina and Cabrera de Mar and the vaulting pots of kilns occur in very different contexts (both economic and architectural) from the nozzle tubes, the following discussion focuses exclusively on the nozzle tubes. Clearly, a major advantage of the small nozzle tubes was that they formed a type of permanent centering and eliminated the need for a sturdy wooden structure to support the wet concrete of the vault.[85] The tubes themselves had to be manufactured at a cost, but using them in place of wooden centering also eliminated the need for skilled carpentry work. Scaffolds, which would still be necessary for building both the walls and vaults, were lightweight temporary structures made of short boards that could be lashed together, whereas centerings for large concrete vaults had to be strong enough to support the weight of the concrete, and they then had to be dismantled and lowered. The shell of tubes eliminated this procedure and allowed for the construction to continue without interruption.

Other suggested reasons for using the tubes include the following:

1) to enhance insulating properties[86]
2) to reduce the weight of the vault[87]
3) to provide certain structural advantages[88]
4) to eliminate centering, which would be costly because of the dearth of available wood[89]

The first reason (insulation) is doubtful for a majority of the examples because the tubes are used in a variety of different building types such as tombs, cisterns, and houses that do not require insulation. Indeed the earliest examples seem to come from tombs. Lézine cites an unusual example at Carthage of a small underground space (0.75 m wide, 0.98 m tall) in which both walls and vaults were made of interlocking tubes that could have been used for insulation,[90] but it is anomalous.

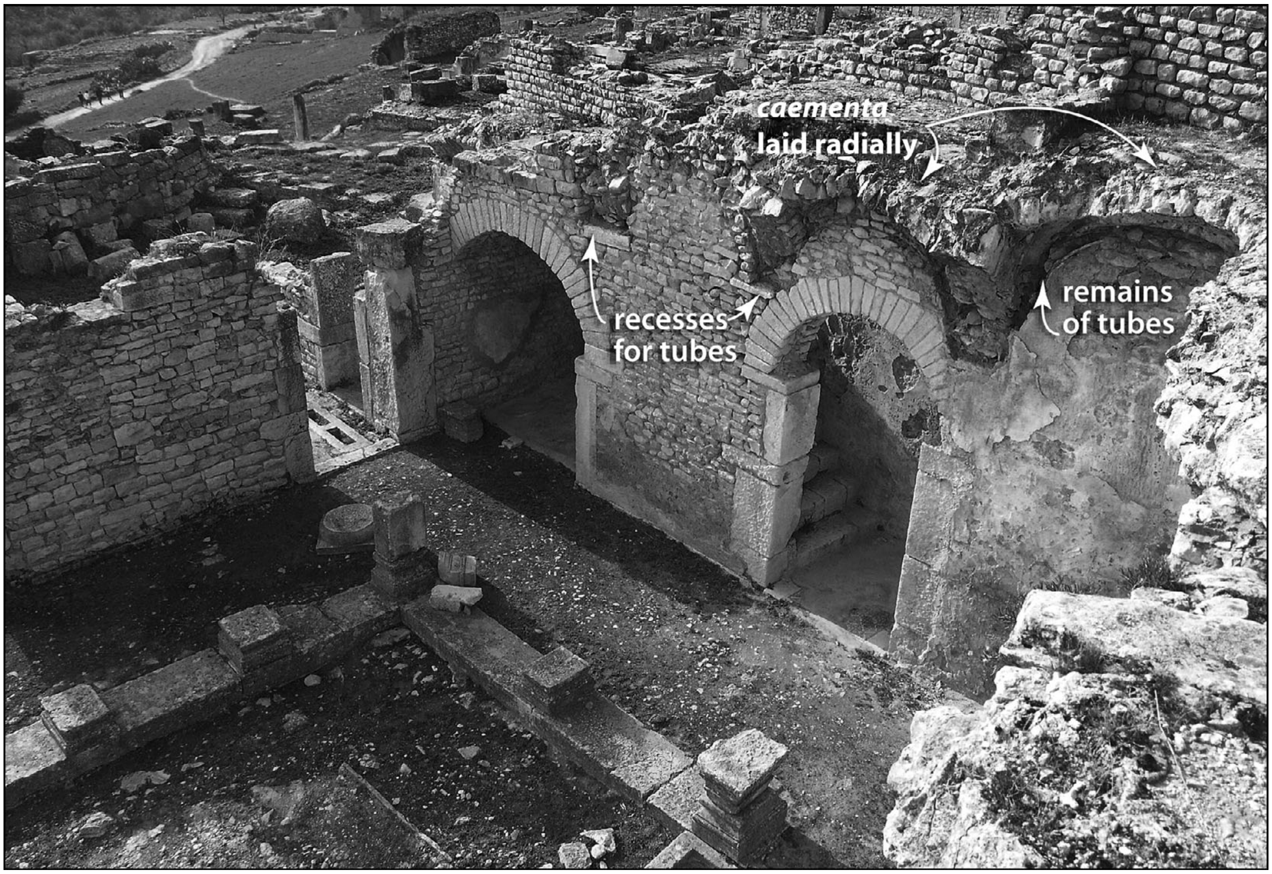
The second idea (weight reduction) is one that has developed from the confusion between using vaulting tubes as permanent formwork and building amphoras into the core of the concrete of the vault, as explained at the beginning of the chapter. In the early examples from the second and third centuries, the tubes were always used as formwork for concrete, and because they were often filled with gypsum mortar, they would have provided little advantage in terms of weight reduction.[91] The one exception could be when they were employed for small cross vaults where the tubes formed a large proportion of the vault in relation to the stone and mortar fill (see Chapter 8).

The third idea (their structural advantages) is certainly relevant to the use of tubes to create lightweight shell vaults (see the later discussion), but that only occurred in the fourth century[92] and was not a factor in the initial proliferation of the technique. However, a question arises: To what degree did the builders see the permanent tube linings as a structural element for concrete? One issue related to this question is the way in which the *caementa* were set above the tubes. As we saw in Chapter 2, there were a variety of methods of setting the *caementa*, from large slab-like voussoirs to randomly placed small stones (Figs. 14–16). A survey of the tube vaults reveals that many had the *caementa* set radially in spite of the tube-lining as in the House of Dionysus and Ulysses at Dougga (Fig. 77, WebFig. 26) or the Baths of Memmia at Bulla Regia (Fig. 15A, WebFig. 24). At the latter, some of the vaults were built with tube formwork and others with wooden formwork, yet both types have the *caementa* laid radially. This suggests that the builders conceived the long-term structural behavior of both types of vault to be the same.

The fourth reason (lack of available wood) requires further elaboration. Two reasons given for the potential dearth of wood are the general absence of forested areas in North Africa and the excessive building during the third century. Northern Tunisia, where the nozzle tubes first appear, is a rich landscape that was the source of much of Rome's grain, but it also sustained forests that were the home of many of the beasts that were hunted for the games and shipped to Rome. An inherent lack of forests due to an inappropriate climate cannot be a cause; however, progressive deforestation is possible.[93] The desire to take over forested lands was what prompted the petition recorded in the Aïn-el-Djemala inscription, mentioned earlier. In fact, Tertullian, a Christian from Carthage who was writing in the early third century CE, provides some idea of the effect of the legal incentives to take over unused land:[94]

> Wildernesses have been replaced by most charming estates, forests have given way to plowed fields, herds have made the wild beasts retreat, desert sands have been reclaimed, stones have been plowed under, and marshes drained.

His description suggests that a certain amount of deforestation had occurred in order to create more cultivable land. Wooden boards were surely used on



77. House of Dionysus and Ulysses at Dougga (ancient Thugga), Tunisia (second half of third century CE). Photo of remains of cross-vaulted portico built on shell of vaulting tubes. (Color image: WebFig. 25).

building sites for scaffoldings and other purposes, but if the large timbers had to come from farther afield as forests were reclaimed, transportation costs could have become a factor. The kilns for firing the tubes, in contrast, did not need the forests for fuel, which was supplied by olive branches, olive pits, and cakes made from the refuse from olive oil processing.[95]

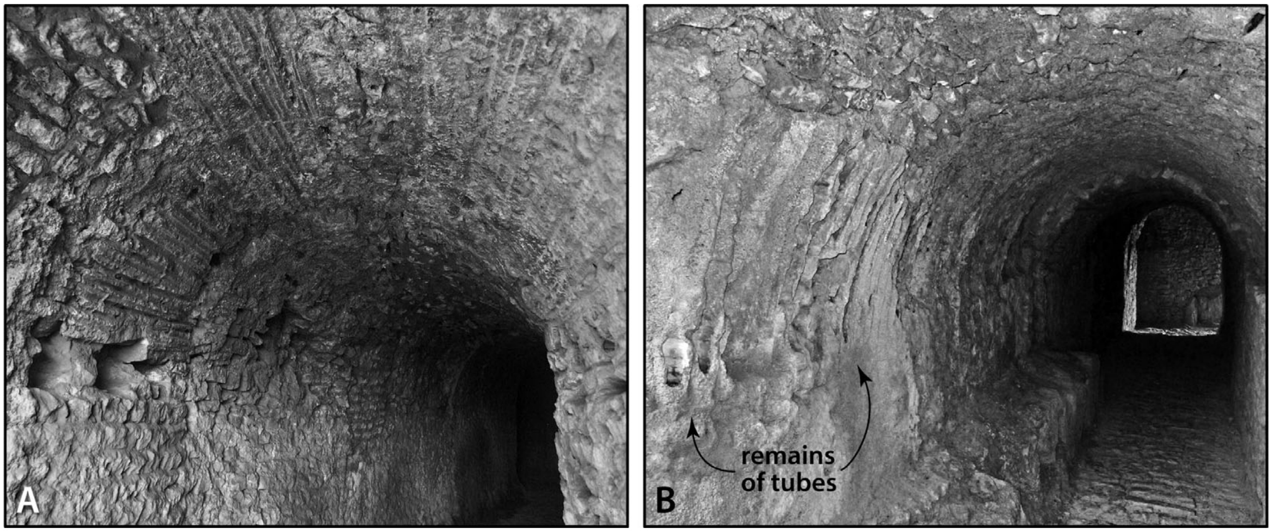
The choice to use the tubes was probably not simply due to a lack of wood, but rather to changing economic dynamics involving a variety of factors, including the availability of materials, personal relations with suppliers, and the nature of the available workforce. Unfortunately without stamps or fabric analyses to enable the tracing of workshops or clay sources, we do not know how far the tubes typically traveled from their place of manufacture or who supplied them. However, evidence from other classes of terracotta building elements provides insight into the factors at play. J. DeLaine's study of brick stamps at Ostia reveals the web of interpersonal relationships that were involved in the procurement of materials for projects there.[96] We get a hint of such connections at work in North Africa with the importation of bricks from Rome that were made in the *figlinae* of the brothers, Cn. Domitius Lucanus and Cn. Domitius Tullus.[97] Both were proconsuls in Africa Proconsularis under Domitian, and D. Kehoe has argued that the *saltus Domitianus* mentioned in the Ain el-Djemala inscription, discussed earlier, refers to their property.[98] The architecture of Africa Proconsularis rarely employed bricks, which usually only appear in bath buildings, particularly in hypocausts. Numerous examples of bricks made in the Tiber valley *figlinae* owned by the *gens Domitia* have been found at Carthage and elsewhere (one each at Leptiminus and Uthina).[99] The appearance of these imported bricks, which are associated with known senatorial landowners in the area, suggests a network of personal connections that brought them there.

Similar types of personal connections at the local level could have been a factor influencing the choice to use the vaulting tubes. Many of the patrons of urban structures employing the vaulting tubes may well have owned property on which the tubes were produced or had personal relationships with the producers, as through the institution of *clientela*. This type of relationship is one of the hidden factors that cannot be traced without the benefit of stamps, but it is one that could have affected the decision to go with a formwork of tubes or of wood. Once North Africa became a center of production both of agriculture and terracotta, the ties that bound patrons, builders, and material suppliers must have become much more complex than they had been in the early second century CE. From a purely economic perspective, the vaulting tubes would have offered a viable alternative to timbers if they were produced within a system that was already highly developed for large-scale production of other ceramic items, so that materials, transport, and labor were already established. Personal preference (or personal gain) may have tipped the scales one way or the other, but clearly in North Africa they tipped toward the tubes quite often.

Some large projects employed several types of formwork: vaulting tubes, wooden boards, and reed mats (laid over a wooden structure). The "Licinian" Baths at Dougga (211–217 CE) have evidence of all three types. The tubes and the reed mats were both used in different parts of the substructures (Fig. 78, WebFig. 26),[100] which suggests that different work groups may have chosen to use different methods and materials. The Baths of Julia Memmia at Bulla Regia also have some vaults built with formwork boards and others built with tubes (Fig. 79). One suggestion has been that the tubes were reserved for less humid rooms because gypsum is susceptible to water damage,[101] but the evidence from the Baths of Memmia does not support this idea, because the wooden formwork occurs in the drier area of the entry vestibule (rm 5). Unfortunately many of the heated rooms do not preserve their vaults. In any case, this is not a pattern that can be traced in other bath structures. For example, at Aquae Flavianae the tubes were used in the two major pool rooms (Fig. 73). The size of the vault is another possible criterion for choosing the tubes. At the Baths of Memmia, the two vaults employing wooden centering are the largest with spans of 8 and 11 m, the latter of which rivals the large cross vault of tubes at the baths at Thelepte (11.6 m span). Perhaps the builders responsible for these two vaults were not confident in using the tubes for such spans. At the "Licinian" Baths, however, the use of different techniques in a similar situation seems more likely a result of different work groups making different choices, which could be due to various untraceable factors related to supply sources and personal connections.

EFFECTS ON ARCHITECTURAL SPACE

Once vaulting tubes became common in North Africa they began to have an effect on the way people conceived their built environment. This idea is perhaps best represented at Bulla Regia, known for its unique houses furnished with cool underground *triclinia* (dining rooms) and *cubicula* (bed rooms), which would have been a welcome refuge in a region

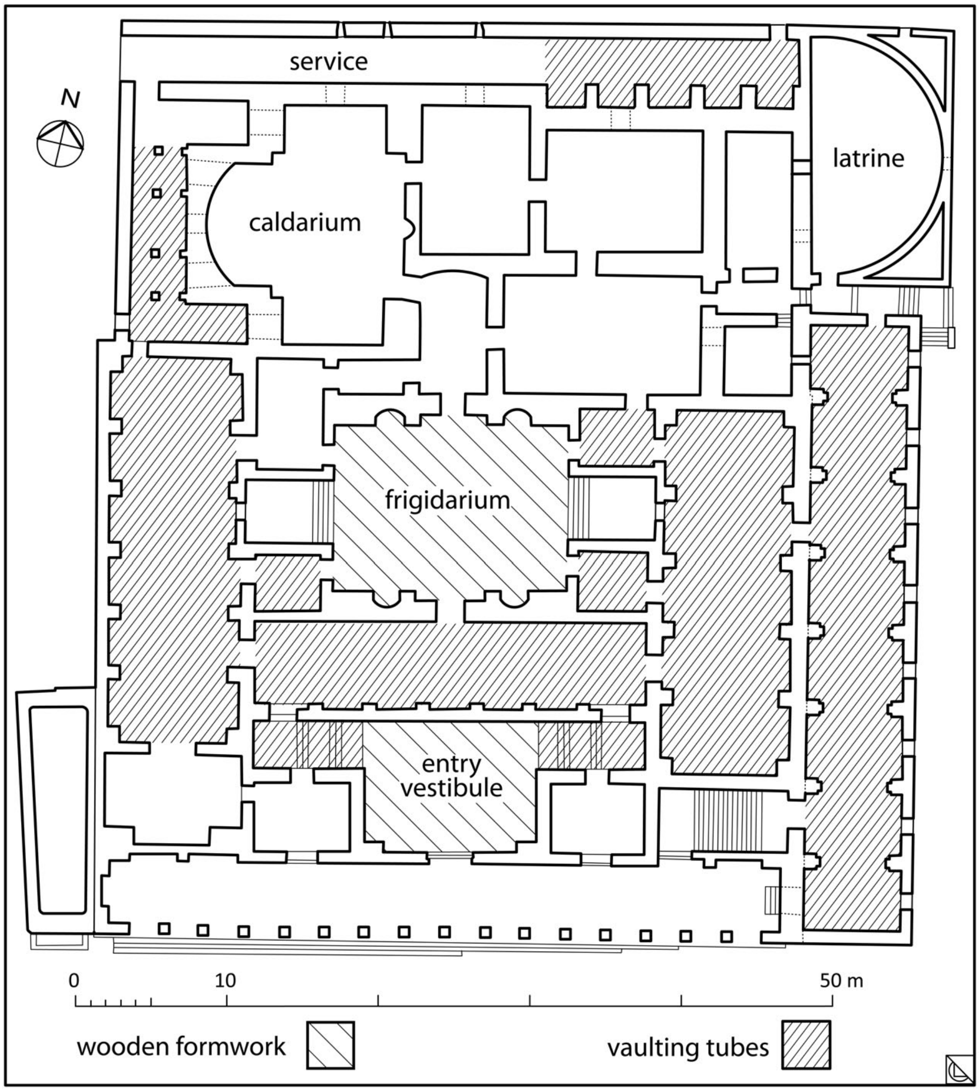


78. "Licinian" Baths at Dougga, Tunisia (211–217 CE). Two substructure galleries built using different techniques. A: Vault with impressions of reed mats along intrados. Centering holes visible at left. B: Vault with remains of vaulting tubes along intrados visible at left (photo: Miles Lewis). (Color images: WebFig. 26).

where the temperature can reach 50°C in the summer. There are nine examples of houses with these underground rooms, and in all but one their vaults were built with vaulting tubes.[102] The one without the tubes, the House of Fishing, is the earliest and has been dated to the first half of the second century based on the style of its mosaics and the fact that it does not use the tubes.[103] Most of the others with tubes probably date from the third century on stylistic grounds.[104] The easily excavated alluvial soil at Bulla Regia made the underground rooms possible. Thick retaining walls were built both to counter the pressure of the soil and to support the vaults that formed the floor of the rooms above at ground level.[105] The idea to build underground occurred before the tubes were common, but it only took off after they were easily available.

One of the largest and most elaborate examples is the House of Amphitrite. The underground *triclinium* was covered by a cross vault (5.0 × 5.9 m) where the tubes have fallen away, leaving only the impressions in the concrete (Fig. 80). In this case, the deeper impressions along the groins demonstrate one of the complications of building a cross vault using the tubes. The tubes can only join with each other in one direction, so there was no way to connect them along the groins aside from the gypsum mortar. So, to reinforce this weak point, the builders added another row or two of tubes to "glue" them all together as the vault was going up. The added thickness at the groin reinforced it so that the forces, which were concentrated at the corners, could be transferred to the wall as the wet concrete was added above. To increase the rigidity of the shell the builders often added an extra layer of tubes along the edges where the vault met the wall. The crowns were also thickened where the diagonal ribs met to hold everything together at the top.[106]

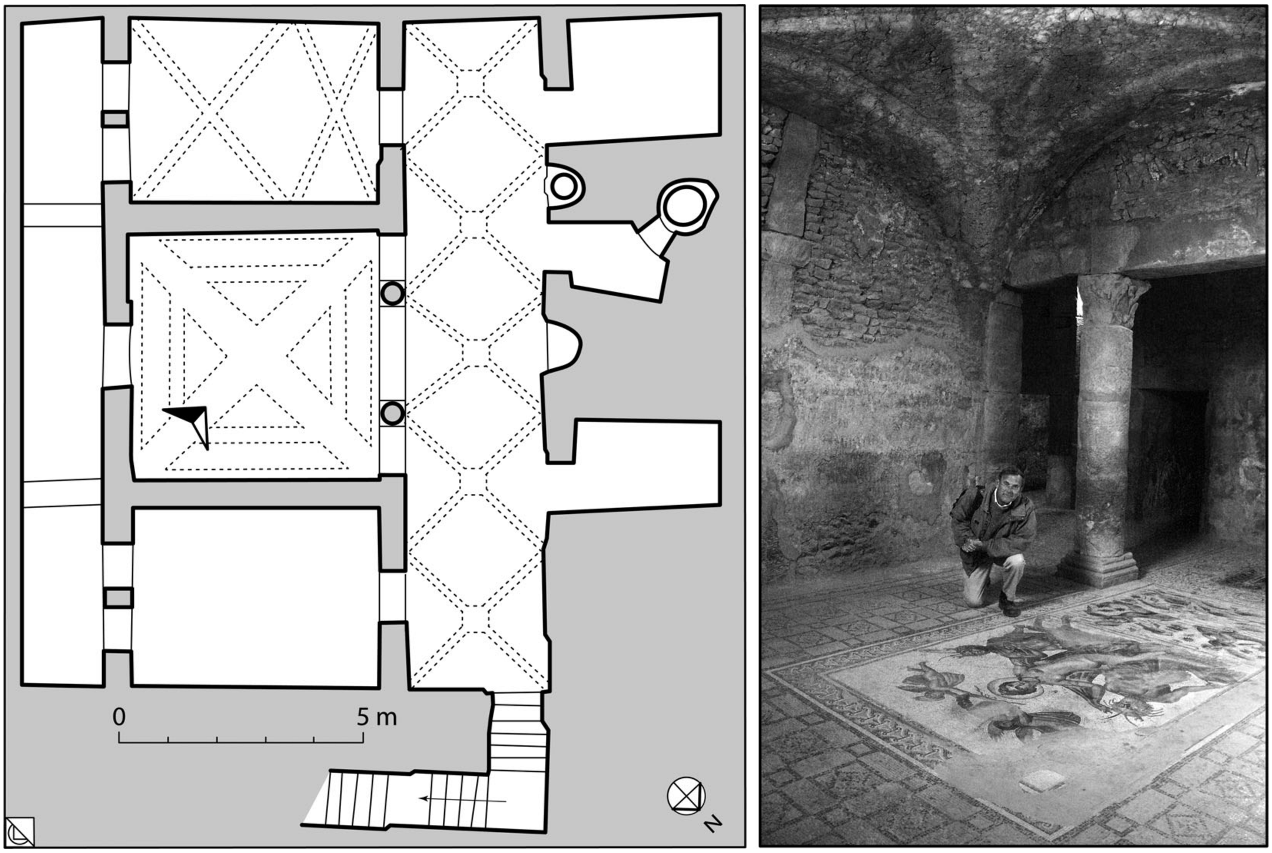
Using the tubes would have virtually eliminated the wooden centering that would have otherwise hindered access to these confined underground spaces and then would have had to be removed. At the House of Amphitrite the staircase leading up to ground level, which had a right angle turn, was the



79. Baths of Julia Memmia at Bulla Regia, Tunisia (c. 230 CE). Plan showing locations of tube centering and of wooden formwork (based on reconstruction in Broise and Thébert 1993: fig. 1).

only means of egress once the vaults were added. The underground rooms were luxurious entertainment spaces, as demonstrated by the floor mosaic of Amphitrite that gives the house its name (Fig. 80). Some even face onto sunken open courts complete with tinkling fountains. The underground rooms are unusual and would have changed the ritual of entertaining and the way in which the elite in Bulla Regia received their guests. Presumably they had some cachet, especially in mid-summer. Thus the popularity of this singular house type for the wealthier members of the community was apparently influenced by both the environmental conditions and the building materials available to facilitate the construction process.

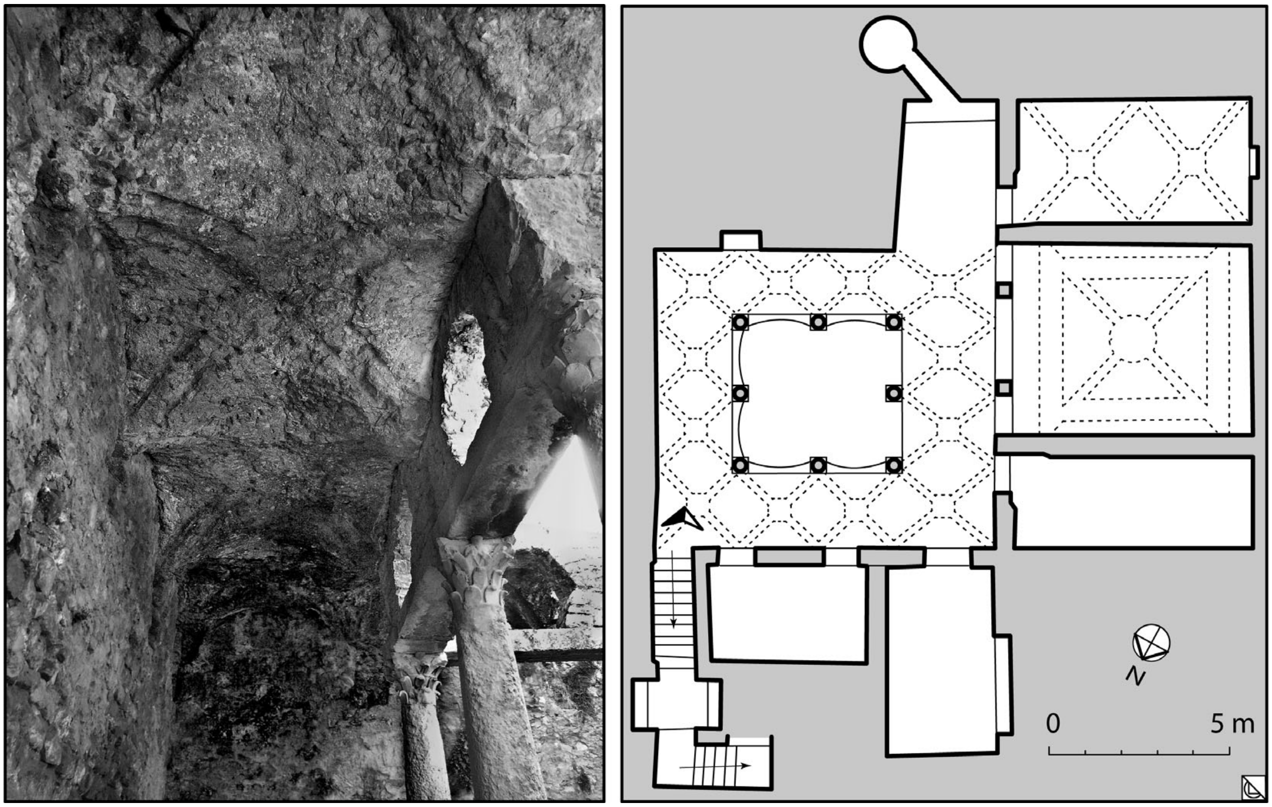
Another house at Bulla Regia that illustrates the utility of the vaulting tubes for creating elegant underground entertainment areas is the House of the



80. House of Amphitrite at Bulla Regia, Tunisia (first half of third century CE). Reflected ceiling plan (left) of underground portion of house showing pattern of tube vaulting (ceiling plan of main room after Lézine 1954, fig 7.2; patterns in other rooms estimated from personal photos and site sketches). Arrow indicates camera location for photo (right) of the *triclinium* showing the impressions left in vaulting from the tubes.

Hunt, where the underground rooms face onto a columned peristyle. The house has been excavated, and though no detailed report has been published, Y. Thebert provides an overview explaining that the peristyle was built in the early third century CE on top of earlier structures and that the surrounding vaulted rooms were added at this time.[107] Other houses had light wells, but the House of the Hunt is the only one that takes the form of a columned portico (Fig. 81). Like the atrium in the Domus at Terrace House 1 in Ephesus (Fig. 50) discussed in Chapter 4, this portico (2.5 m span) was covered by vaults. In this case, the cross vaults were built on a shell of tubes, rather than on a shell of brick, but the structural situation is similar – both have vaults supported on columns. The brick sail vaulted porticos never became very common in Asia Minor, but the cross-vaulted porticoes built with tubes seem to have started a trend in North Africa, which as seen earlier, may have even been exported to Dura-Europus along with the idea of the tubes.

Dougga, located 45 km southeast of Bulla Regia, provides examples of the variety of structures that employed the tube vaults for porticos in above-ground contexts. The House of Dionysus and Ulysses, which was built on the side of the hill on

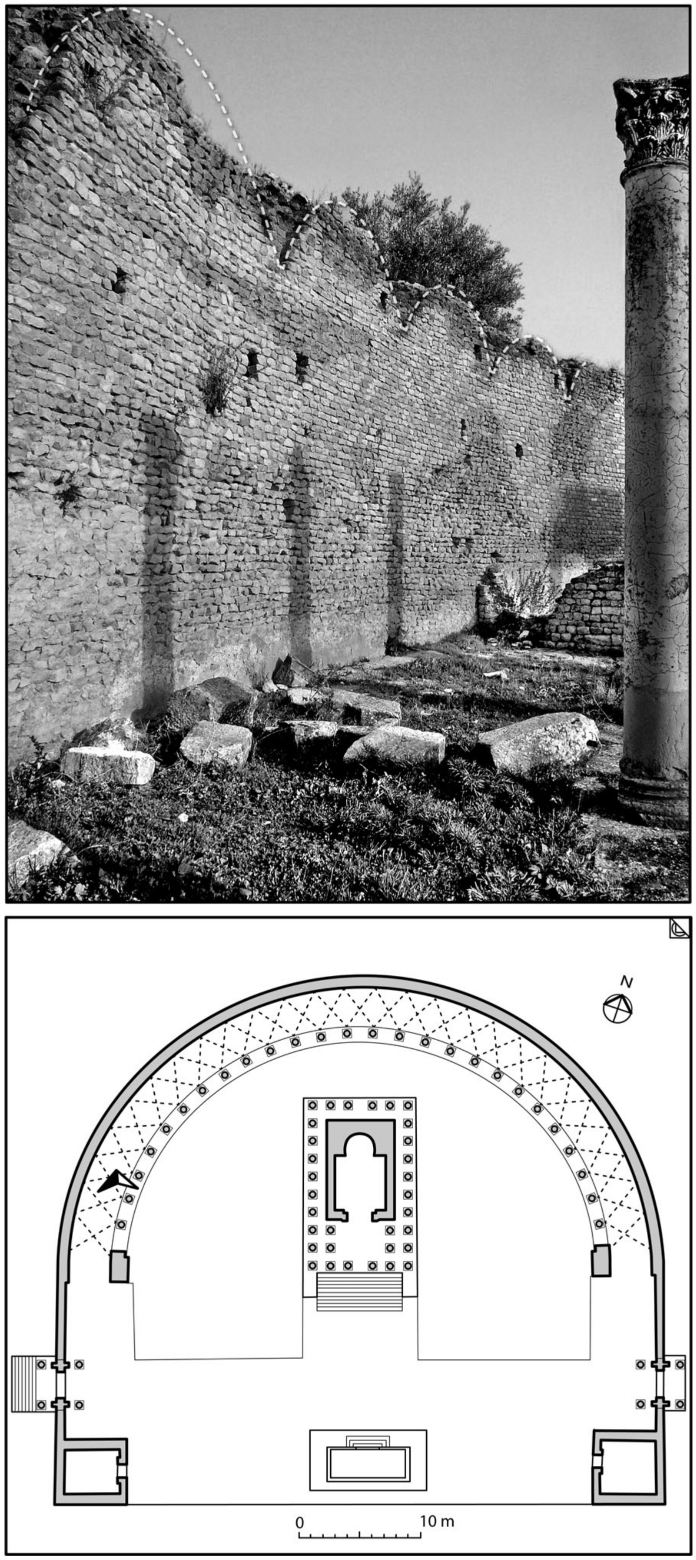


81. House of the Hunt at Bulla Regia, Tunisia (early third century CE). Reflected ceiling plan of underground rooms around sunken portico (ceiling plan of the main room after Lézine 1954, fig 7.3; patterns in other rooms estimated from personal photos and site sketches). Arrow indicates location of photo (left) showing where the groins of the cross vault were reinforced with an extra layer of tubing (now fallen).

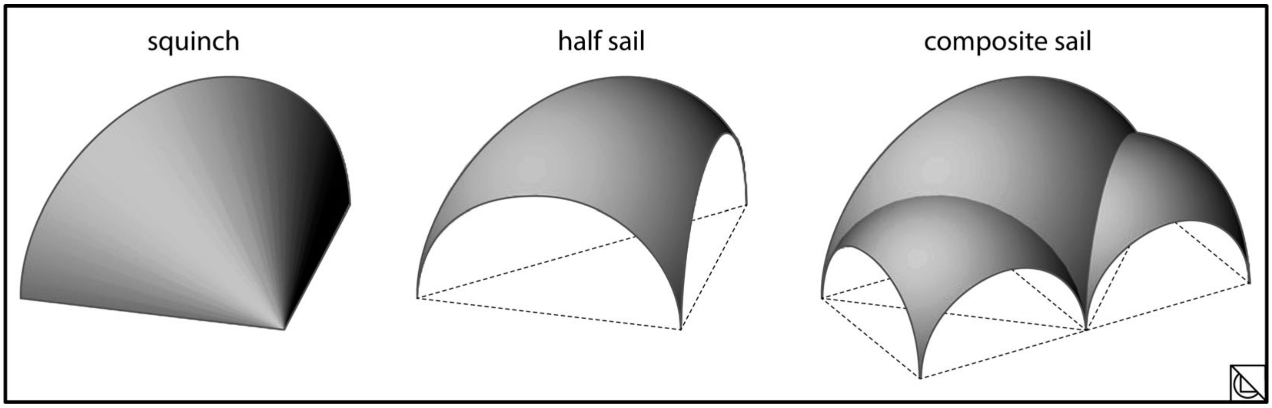
which the town is perched, has a peristyle similar to the underground one at the House of the Hunt in Bulla Regia. It is not as well preserved, but the spring of a few of its cross-vaulted bays is still visible (Fig. 77, WebFig. 25). The house south of the Temple of Tellus had a similar arrangement. At Dougga, porticos with cross vaults of tubes are also evident in public structures, such as the "Licinian" Baths and the Sanctuary of Juno Caelestis (Fig. 82). The entry portico of the "Licinian" Baths (2.0 m span) has been rebuilt, but the remains of tubes were recorded there before the modern reconstruction occurred.[108] The sanctuary enclosures do not preserve the tubes, but the tell-tale setbacks on which the tubes rested remain at the Sanctuary of Juno Caelestis (3.9 m span, 222–235 CE).[109] The taste for such porticos does not seem to have been limited to the Medjerda valley, as shown by the early Severan example from Aquae Flavianae (208 CE) (Fig. 73). In Rome, one only finds vaulted porticos in imperial structures, such as the imperial thermae, the Basilica Ulpia, and at Hadrian's Villa, but the introduction of the tubes in North Africa resulted in a new style that was adopted in both public and private contexts.

A NEW VAULT FORM IS BORN

In addition to modifying architectural trends, the introduction of the vaulting tubes also led to the creation of a new vault form peculiar to Africa



82. Sanctuary of Juno Caelestis at Dougga, Tunisia (222–235 CE). Top: Remains of setbacks for tubing of cross vaults covering annular portico are visible along the back wall. Bottom: Dashed line indicates original line of vaults (reconstructed plan based on Golvin and Khanoussi 2005: fig. 171).

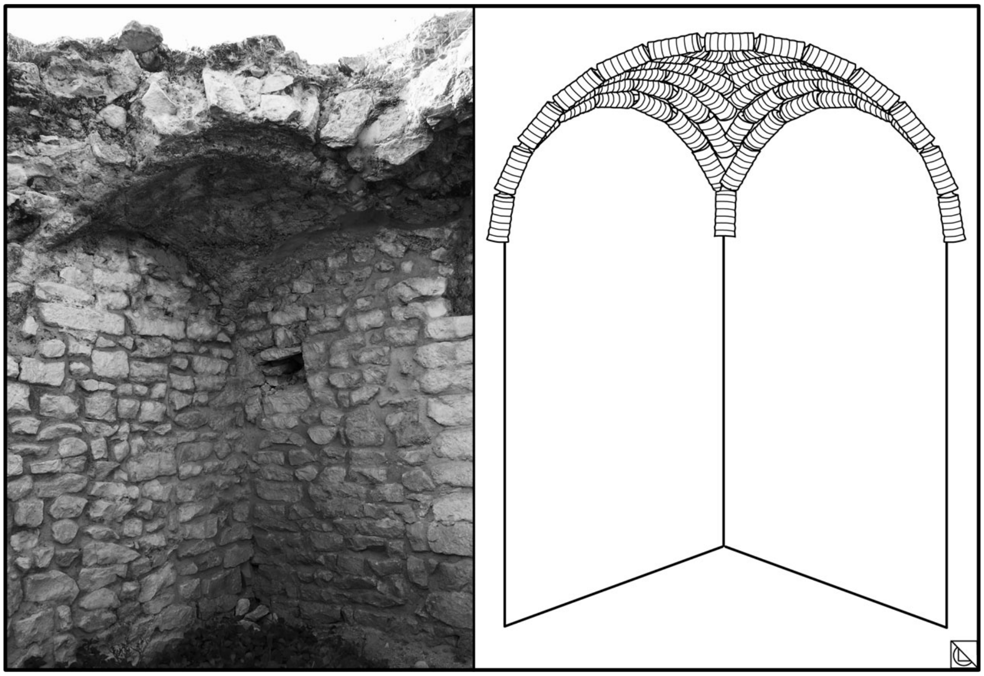


83. Diagrams of geometry of the squinch vault, the half sail vault, and the composite sail vault. Only the half sail and composite sail vaults were used with vaulting tubes.

Proconsularis, which Storz calls the North African "*Tromphengewölbe*" in his monograph on the vaulting tubes. This German term, which translates literally to *trumpet vault* in English, has traditionally been used to describe the conic vaults that I referred to as *squinch vaults* in Chapter 4. However, as Storz notes, this new form that appears in North Africa is different from the earlier ones; it has a spherical shape formed from a square sail vault that has been cut along the diagonal (Figs. 83, 84). Using the same term to describe both geometries leads to misconceptions regarding the origins of the North African type, so I refer to it as a *half sail vault*. This hybrid form was born directly from the construction method employing the tubes. The way they were put in place enabled the spherical form to be created easily and without formwork (Fig. 84), and the small size of the tubes allowed for the combining of more than one vault to create new complex shapes that appeared nowhere else. Thus far the only confirmed examples occur in Tunisia at Carthage and in the Medjerda valley at Chemtou and Dougga, though Storz cites a possible example at the baths at Thelepte.[110]

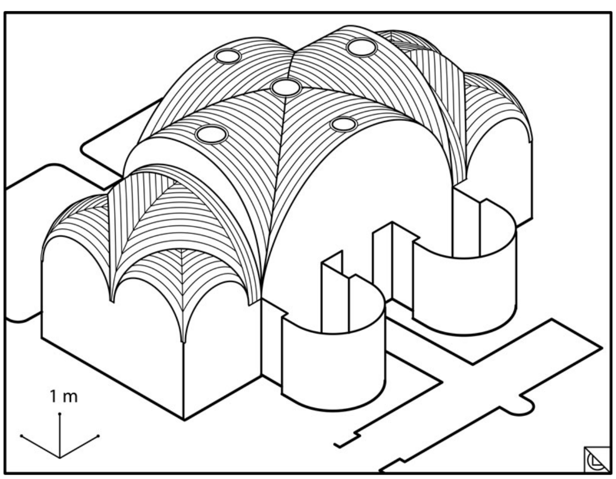
The half sail vault at Chemtou is the simplest and perhaps earliest. It belongs to a small hydraulic structure (c. 2 m square) in a bath; thus it is not in a high-prestige context. For this reason Storz reasonably speculates that it is an early experimental example. It forms the square end of the room while a semidome covers the opposite apsidal end. It has a *terminus post quem* of the early Severan period when the aqueduct was installed and thus probably dates from some time during the third century.[111] The half sail vaults at Dougga are more elaborate. In the House of the Ducks and Seasons, the upper level terrace is supported by rooms covered by vaults made up of a number of half sail vaults (WebFig. 27), which I call a *composite sail vault* (Fig. 83). They consist of half sails over the corners with a larger sail vault covering the whole space. The mosaics that give the house its name have been dated stylistically to the third century.[112]

The best preserved and stratigraphically dated example of the type of composite sail vaults seen at Dougga was found in Carthage at an underground site known as Kobbat Bent el Rey, where the main room consisted of the central cross vault (3.75 m span) with composite sail vaults covering the rectangular spaces at either end (Fig. 85). Excavation of the site provided a date of 320–340 CE.[113] The space was originally decorated with mosaics and fountains and may have been some type of meeting place for the *sodales*, the clubs that organized the animal fights in the amphitheater, because a graffito



84. Baths of the Cyclops at Dougga, Tunisia (first quarter of third century CE). Left: Remains of half sail vault built with vaulting tubes. Note the radial *caementa*. Right: Reconstruction of tube configuration. This vault was once part of a larger composite sail vault.

representing their symbols was found there.[114] The forms used at Kobbat Bent el Rey are no more advanced than those already found Dougga, but the



85. Kobbat Bent el Rey at Carthage, Tunisia (320–340 CE). Author's drawing showing the geometry and tube configuration of the central room of the underground space (based on survey drawings from Storz 1994). The holes in the cross vault indicate circular light wells.

complete preservation of the former provides a much better sense of the space created than the earlier damaged ones. These are complex forms that would not have been attempted with regular wooden formwork – they are a direct result of using the tubes. In Rome, the invention of new complex vault forms is usually found in imperial structures, such as the umbrella vaults at Hadrian's Villa, but the tubes provided an easy way to build complex forms at a small scale in private contexts. The main challenge was mastering the layout of the form, but otherwise the construction was quite simple.

In his discussion of the origins and influences on the development of the composite sail vault, Storz cites the third-century Sasanian examples at Firuzabad as a possible source of inspiration,[115] but those vaults are conic rather than spherical. In contrast, the patterns in which the tubes are placed within each individual half sail vault are similar to the patterns used for pitched brick in the first-century mud brick sail vaults in Karanis and in the second-century fired brick examples at Ephesus (Fig. 51) and Epidaurus (Fig. 56). Hence the composite sail vaults in North Africa, which appear by the third century, were more likely to have been inspired by the forms and methods being used for the brick vaults in Greece and Asia Minor than by the Sasanian squinch vaults. The significant difference between the pitched brick and the vaulting tube techniques is that the small size of the tubes allowed for increased versatility, enabling the builders to go on to create a completely new form of vault by combining various sections of sail vaults together into a composite form.

ADVENT OF LIGHTWEIGHT SHELL VAULTS

The final transformation of the tube vaults came in the fourth century when the vaulting tubes began to be used to create lightweight shell vaults instead of permanent centering for concrete vaults. One of the earliest datable examples occurs in the early fourth-century Crypta Balbi in Rome where the previous ceiling had consisted of a 10.5 m wide hanging barrel vault of plaster suspended from the wooden floor beams of the room above. When it was replaced, the builders divided the portico into more manageable spans by adding intermediate piers and then covering the two aisles with cross vaults made of tubes. This also provided the advantage of being easily assembled under the existing floor beams by working from below.[116] The choice in this case seems to have been dictated by an existing condition that had to be respected.

During the fourth century the use of the lightweight tube shell vaults became more common in Italy and North Africa, as can be seen in the mid-fourth-century Sanctuary of the Syrian Gods on the Janiculum in Rome and in a number of Christian structures from the second half of the fourth century: the Basilica Ursiana in Ravenna, the Christian basilica at Hippo Regius, and the first basilica at Sufetula (modern Sbeitla).[117] The new method of employing the tubes to create lightweight vaults was particularly adaptable for the new Christian basilica form. It provided an easy and economical way to create lightweight, curvilinear apsidal forms that could be covered with the same type of wooden roof structure as that over the nave and aisles. However, the traditional manner of using the vaulting tubes for permanent centering for concrete vaults continued, as seen in the mid-fourth-century example of Kobbat Bent el Rey in Carthage, discussed earlier.

CONCLUSIONS

The vaulting tube underwent a long period of development and refinement stretching from the third century BCE with the first appearance of the bullet-shaped tube to its final form of the nozzle tube used to create lightweight vaulting in the fourth century CE. The vaulting tubes at the third-century BCE bath at Morgantina and at the second-century BCE bath at Cabrera de Mar both used intricately fashioned terracotta elements, each with a bullet-shaped form made specifically for the context in which it was applied. In both cases iron connectors were employed between some of the tubes. At Morgantina the desire to eliminate centering was probably not the prime motivating factor given the great size and weight of the tubes there. At Cabrera de Mar the use of the iron bars together with the tubes could have been intended to reduce the support structure during construction. However, this does not explain the initial choice to use the tubes. More probable is that the tubes represent early attempts at creating a solid roofing system that would be resistant to damage from fire and moisture. In her discussion of the invention of the vaulting tubes for the bath at Morgantina, Lucore suggests a direct influence from Syracuse where Hiero II ruled from 270 to 215 BCE. Syracuse also had baths from the same period, which may have had some form of tubular vaults as well, though definitive evidence is lacking. Lucore also notes that the intellectual milieu of Syracuse in the mid-third century BCE was heavily influenced by its star mathematician and inventor, Archimedes.[118] Whether or not the great inventor himself was involved in the conception of the first tube vaults is impossible to say,[119] but certainly a great thinker can have the effect of generating an ambience that affects those around him, and eastern Sicily was clearly a creative center under Hiero II.

Vaulting tubes were used at the bath at Cabrera de Mar (mid-second century BCE) and again at the bath at Perpignan a century later, but by and large the use of this technique of interlocking hollow elements shifts to kiln construction. The earliest example of purpose-made vaulting pots for kiln roofs is at Marcianella in the second half of the second century BCE, by which time *opus caementicium* was making its appearance in Italy and providing a solid and waterproof alternative for baths. Vaulting pots were then used in kiln construction continuously until the third century CE, especially in Italy and along the Rhine in both military and civilian potteries. In Pompeii, one finds both kilns employing vaulting pots and an experimental use of water-pipes in the vault of a house, which puts the two ideas together in one place in the years before the 79 CE eruption. For the later nozzle tubes, finding a direct connection with kiln construction is difficult because very few North African kilns have been excavated; those that have been excavated belong to a period after the initial idea had come about, but none reveals any sign of having employed the vaulting pots. However, the fact that the tubes began to appear shortly after African Red Slip (ARS) A began to be produced in northern Tunisia suggests that the movement of potters from Europe could have been a mode of transmission. The vaulting pots were especially common in pottery workshops along the Rhine, and the importation of Gallic and Italian forms in the new ARS production of the late first century CE implies the transfer of ideas between North Africa and northern Europe where these types of kilns are known to have been used.[120]

One of the critical elements in the transition from kilns to larger architectural structures is the use of quick-setting gypsum mortar, which allowed the nozzle tubes to be put in place without centering. Tunisia is full of gypsum deposits in both the north and central zones because of its geological history. Gypsum is an evaporite that is typically created by climate fluctuations in which saline water collects and then evaporates in an arid or semiarid environment so that the gypsum precipitates. In the southern areas it occurs in the crusts that form around the chotts. In the northern areas the gypsum deposits are much older because they were formed during the hot dry climate of the Triassic period. The compressive folding of the earth's crust that formed the Atlas Mountains produced outcrops of the Triassic gypsum (245 Ma), as occur near Thurburbo Maius at Djebel Azeis and near Carthage at Djebel Amar.[121] So most places in Africa Proconsularis would have had gypsum deposits fairly close at hand. Ultimately, the development of the nozzle tubes was probably influenced by geological, economic, and human factors that came together in North Africa during the second century CE.

The ubiquitous adoption of the vaulting tubes in Africa Proconsularis eventually affected the architecture in which they were used. The increased agricultural production led to greater wealth, which manifested itself in urban centers. The tubes are found in many different structures from cisterns in the countryside to urban temple and bath complexes and private houses. Two places where the effect of the tubes on architectural design can be seen are Bulla Regia and Dougga, each of which underwent a period of intensive building during the third century, presumably stemming from the wealth derived from the expanded export trade in the province. Once the idea of the permanent tube centering was adapted into a lightweight shell vault on its own, it became a common method of building apses in Christian churches that otherwise had roofs of wooden construction. The development of vaulting tubes thus illustrates the web of interrelated strands that connected the building industry to other sectors of society and how that web changed over time.

A postscript to the development of the vaulting tubes comes in the twentieth century when the French architect Jacques Couëlle patented a similar type of vaulting tube, which began to be manufactured in Marseille around 1940. A dark side of the story revealed itself at the end of World War II when the Nazi concentration camps in Germany were liberated. One of the satellite camps (Kaufering VII) outside Dachau had underground bunkers for housing female inmates – they were roofed with vaulting tubes imported from Marseille, as indicated by the maker's stamps still visible on the tubes.[122] Today, the technique continues to be used in India where vaulting tubes are thrown and fired on site to build low cost structures.[123]

6

HOLLOW VOUSSOIRS

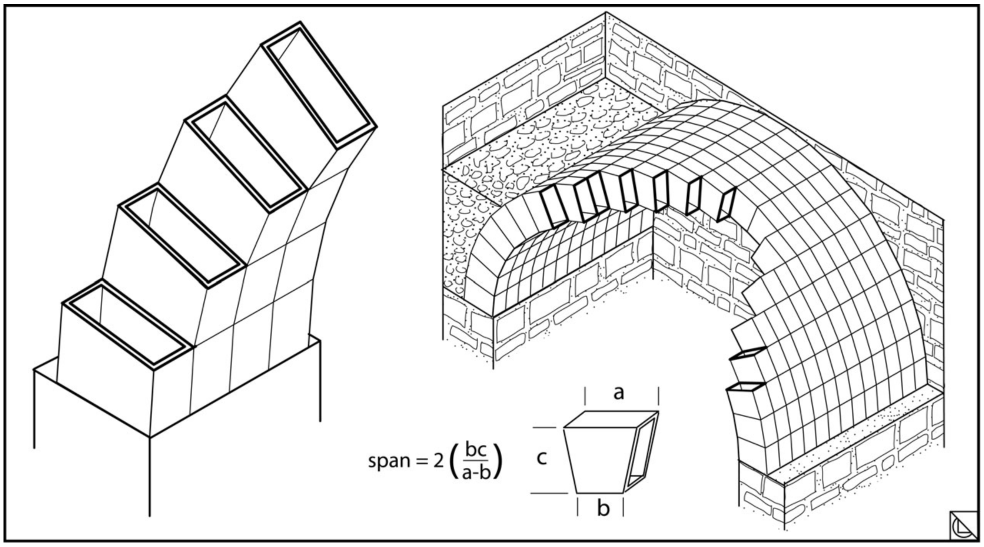
Hollow voussoirs are different from the vaulting techniques discussed thus far because they are used almost exclusively in bath buildings. They were a variation on box-tiles (*tubuli*), which were rectangular terracotta tubes used for heating the walls of bath buildings. Like the box-tiles, they were formed around a wooden mold, but their production was more exacting because they were made in a wedge shape calculated to fit a particular size of vault (Fig. 86). The use of hollow voussoirs is limited primarily to the province of Britannia, a phenomenon that demands explanation (Fig. 87). In exploring why this was so, this chapter touches on issues relating to the conquest and incorporation of this far-flung province into the empire, the role of bath buildings and terracotta production in this process, and the identity of the craftsmen who made the tiles. Questions posed include the following: When and where did hollow voussoirs first appear? Who were the agents behind the invention? What was its intended purpose? How and when did its purpose change? What were the social and economic factors that affected the diffusion of the technique?

ANALYTICAL TOOLS FOR STUDYING HOLLOW VOUSSOIRS

We have three analytical tools available that aid in the study of hollow voussoirs: the use of roller stamps, a formula for calculating vault size from a single tile, and two examples of experimental archaeology involving bath buildings. These tools are unique to the hollow voussoirs and allow us to explore in greater detail the purpose and distribution of this distinctly regional building element.

The practice of impressing patterns on tiles using a wooden roller stamp (much like an enlarged cylinder seal) is critical to tracing the invention and development of the hollow voussoirs. This practice is found almost exclusively in Roman Britain on box-tiles and hollow voussoirs.[1] The dies have been carefully studied and published by a group of British scholars who formed the Relief-Patterned Tile Research Group. Their corpus of dies allows for the dating of particular dies and the tracking of their diffusion, which in turn aids in the study of the hollow voussoirs; therefore, dies used to create relief-patterned tiles (also known as roller-stamped tiles) play a large role in

Catalogs (WebCat.) and color figures (WebFig.) can be downloaded at www.cambridge.org/vaulting

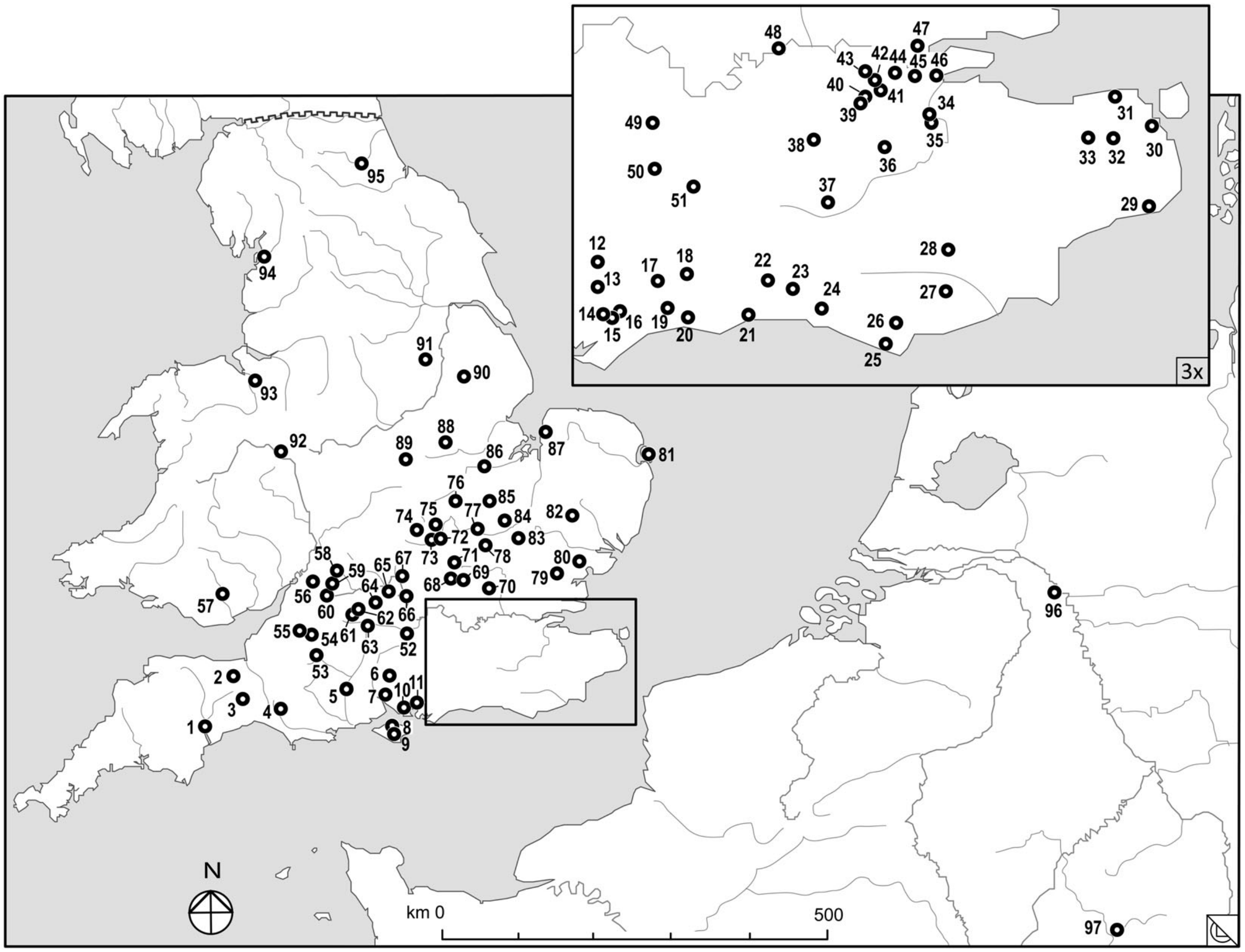


86. Drawing of vault of hollow voussoirs. Formula for calculating the vault span from a given voussoir is shown.

this chapter (Fig. 88). Applying relief patterns with a roller stamp to tiles appears to have been adapted from the similar practice applied to wattle and daub walls as a key for plastering. In Britain, the earliest examples of roller stamps on daub occur in the pre-Boudican (60/1 CE) levels at Colchester, St. Albans, and London.[2] The practice was probably imported from Celtic regions on the continent where examples of roller-stamped daub have been found from as early as the beginning of the first century CE in France, Belgium, and Germany.[3]

The hollow voussoir has a useful characteristic – its wedged shape forms an angle that can be determined and used to calculate the size of the vault to which it belonged even when its original location is not known. The formula illustrated in Figure 86 provides an easy means to calculate the span of the vault by using three basic measurements: upper width (a), lower width (b), and height (c).[4] This is important because none of the vaults made of hollow voussoirs is still standing, and very few have been excavated in situ. In some cases, the voussoirs can reasonably be associated with a particular room or group of rooms in the structure in which they were found, even if they have been disturbed. Likewise, for small villa baths where there are no other potential structures in which they could have been used, their provenance is usually clear, whereas for structures in urban contexts a direct association is not so obvious. The formula thus provides a critical tool for understanding the nature of the structures from which they came.

A caveat must be added regarding the accuracy of the formula – very small discrepancies in measurement can yield much greater discrepancies in span because the error is multiplied by the number of voussoirs making up the arch. Clearly the larger the arch, the greater the possible discrepancy. For a 3 m span, a change of 1 mm in the difference between the upper and lower widths results in a change of 12–13 cm in the span, whereas for a 6 m vault, a change of 1 mm results in a 42–48 cm change of span, and for a 9 m span an 82–102 cm change. Clearly the formula is only as accurate as the measurements, and any slight rounding up or down can create substantial fluctuations that increase along with the size of the vault. Nevertheless, it remains a useful tool for



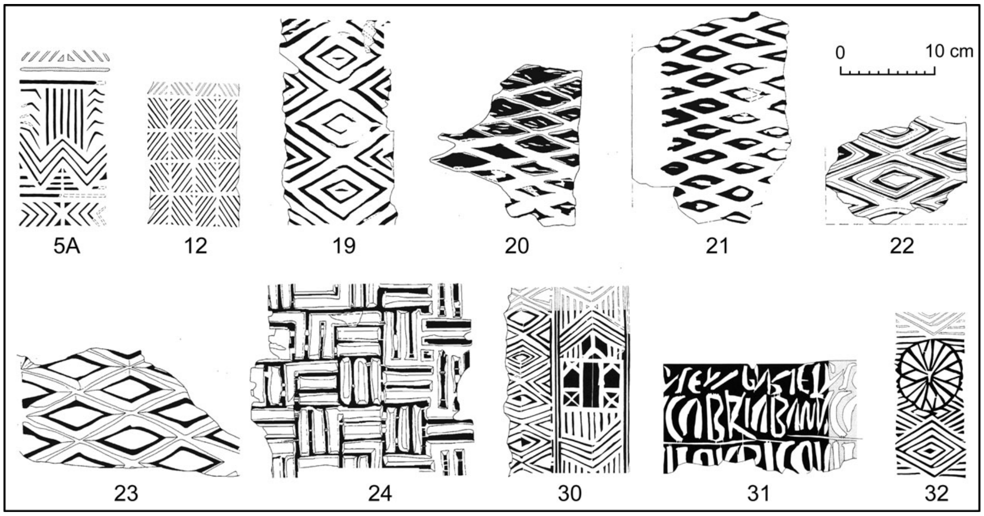
Hollow Voussoir Sites

1 Topsham, **2** Yarford, **3** Whitestaunton, **4** Wraxall, **5** Rockbourne, **6** Winchester, **7** Bitterne, **8** Newport, **9** Brading, **10** Portchester, **11** Havant, **12** Elsted, **13** Chilgrove 1, **14** Fishbourne, **15** Chichester, **16** Westhampnett, **17** Bignor, **18** Wiggonholt, **19** Arundel, **20** Angmering, **21** Southwick, **22** Hassocks, **23** Plumpton, **24** RanscombeHill, **25** Eastbourne, **26** Pevensey, **27** BeauportPark, **28** Bodiam, **29** Dover, **30** Richborough, **31** Reculver, **32** Ickham, **33** Canterbury, **34** Burham, **35** Eccles, **36** Plaxtol, **37** Hartfield/ Little Cansiron, **38** Titsey, **39** Lullingstone, **40** Farningham, **41** Horton Kirby, **42** Darenth, **43** Dartford, **44** Springhead, **45** Chalk, **46** Hamriver, **47** Mucking, **48** London, **49** Ashtead, **50** Binscombe, **51** Wykehurst Farm, **52** Silchester, **53** Warminster, **54** Bradford/Avon, **55** Bath, **56** Stroud, **57** Gelligaer, **58** Chedworth, **59** Cirencester, **60** Oaksey, **61** Badbury, **62** Wanborough, **63** Littlecote, **64** Sparsholt, **65** Frillford, **66** Dorchester, **67** Woodperry, **68** North Church, **69** GadebridgePark/Boxmoor, **70** Parkfield, **71** Totternhoe, **72** Stanton Low, **73** Bancroft, **74** Towchester, **75** Gorefields, **76** Stanwick, **77** Sandy, **78** Radwell, **79** Witham, **80** Colchester, **81** Caister/Yarmouth, **82** Rougham, **83** Great Chesterford, **84** Comberton, **85** Godmanchester, **86** Fengate, **87** West Newton, **88** Thistleton, **89** Leicester, **90** Heighington, **91** Brixworth, **92** Wroxeter, **93** Chester, **94** Lancaster, **95** Binchester, **96** Xanten, **97** Bliesbruck

87. Distribution map of hollow voussoirs (WebCat. 6-A).

examining trends statistically and for determining potential contexts for individual "orphan" tiles.

Finally, we are fortunate to have two examples of experimental archaeology to which we can turn for comparanda. The first is the experimental bath building constructed at Xanten, Germany, in 1989. It was built with a vault of hollow voussoirs (5 m span) on the evidence of some examples excavated from

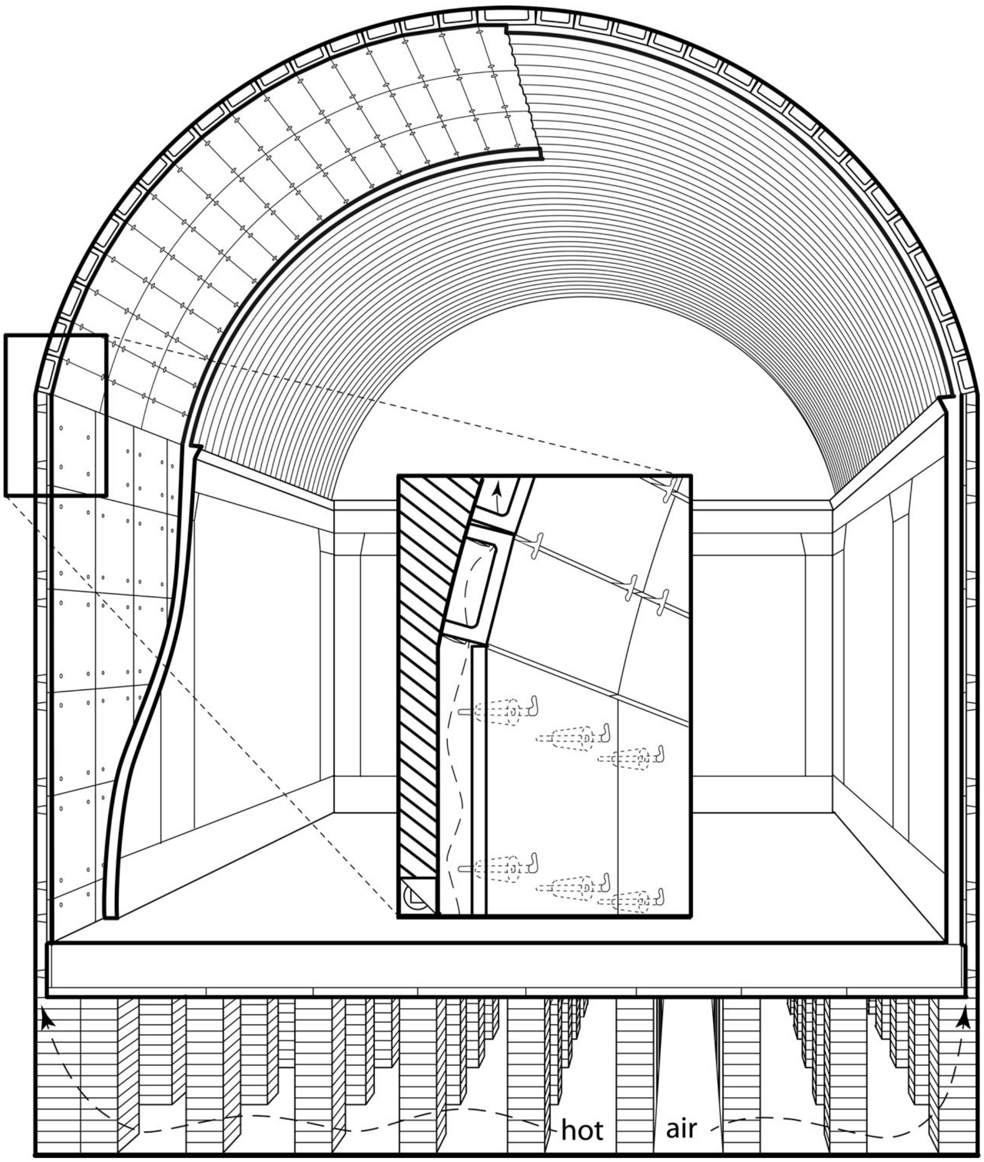


88. Examples of hollow voussoir roller dies mentioned in the text (from Betts et al. 1994; die drawings courtesy of the Relief-Patterned Tile Research Group). Raised area shown in white.

the site of the bath connected to the guesthouse in Insula 38,[5] which thus far is one of only two known examples outside Britain. The second experimental bath building is the one constructed at Sardis in 1998 for the television program *NOVA*.[6] This bath was not built with hollow voussoir vaults, but it did employ box-tiles for the walls, which were monitored by heating engineers to evaluate their performance. Thus the Sardis bath provides a different type of comparanda that is useful in examining the efficacy of the hollow voussoirs as heating elements.

EARLY EXAMPLES

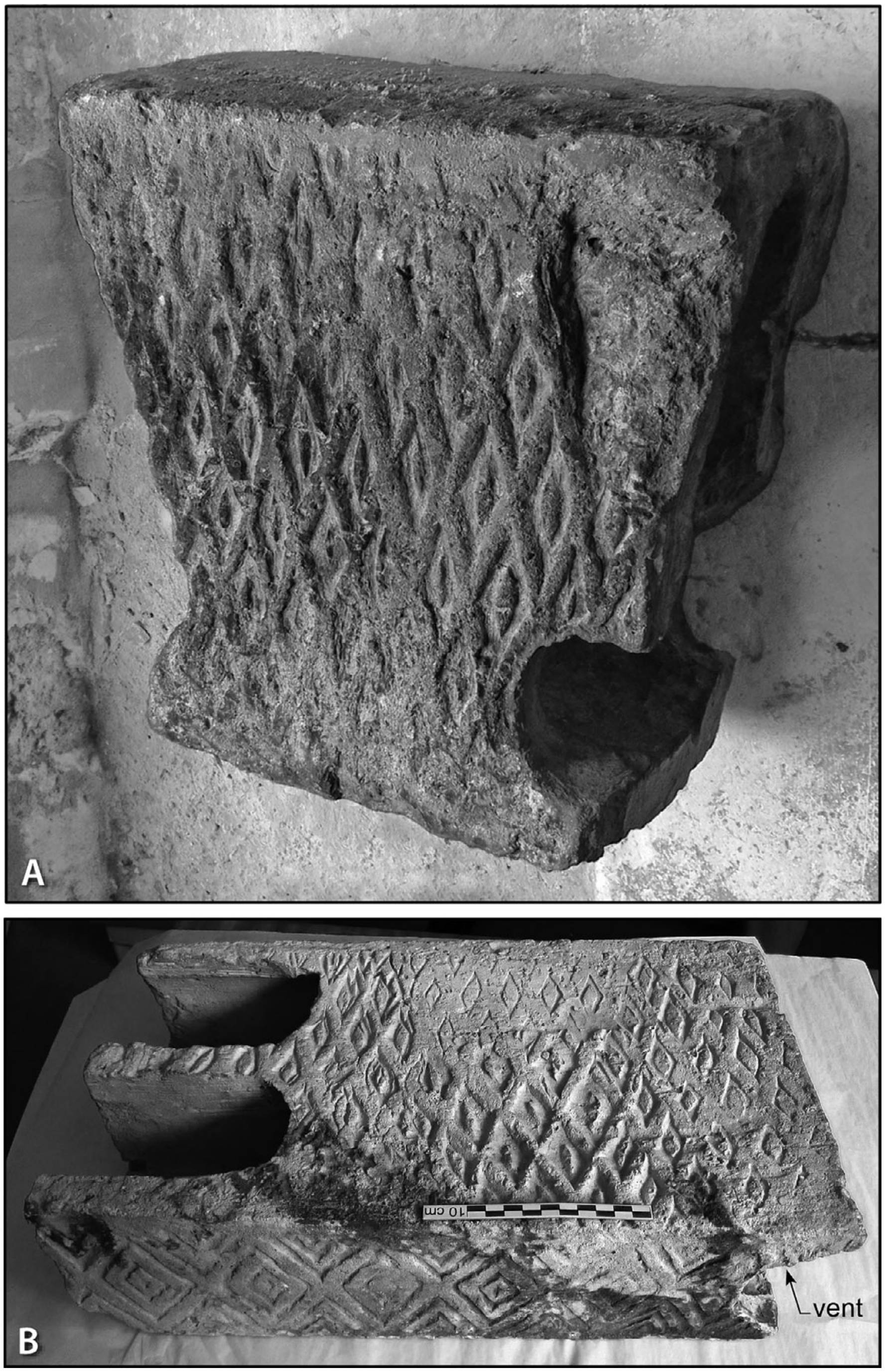
Because the hollow voussoirs developed out of earlier bath heating systems, a brief look at the state of the art in the mid-first century CE provides the context for this invention. The earliest heated walls in Roman baths were created with *tegulae mammatae* as can be seen in the Forum Baths and Stabian Baths at Pompeii, but Seneca, writing in the 60s, notes that box-tiles for heating walls (*impressos parietibus tubos*) were introduced within living memory, which would put their invention some time during the first half of the first century CE.[7] The first method of heating the vaults was to apply the *tegulae mammatae* to the concrete vaults with iron nails, examples of which can be seen at both the women's *caldarium* of the Stabian Baths at Pompeii and the *caldarium* of the Suburban Baths at Herculaneum (Fig. 89).[8] Occasional examples have also been documented (not in situ) for vaults outside of Italy.[9] However, the *tegulae mammatae* created a rather narrow air space (less than c. 7 cm) for the heat, so one has to wonder if the builders were trying to increase heating capacity or simply to reduce condensation. The hollow voussoirs, in contrast, quadrupled the amount of hot air that could be channeled into the vaults, thereby increasing the potential of radiant heating into the room. Another advantage of hollow voussoirs and box-tiles over *tegulae mammatae* is that they allowed for the controlled flow of heat through the tubular channels, which could set up convection systems in which the warm air was recirculated.[10] The use of box-tiles for heating walls was introduced into Britain by the mid-first century CE as demonstrated by finds from datable dump contexts in London, as well as structural remains from the fortress baths at Exeter



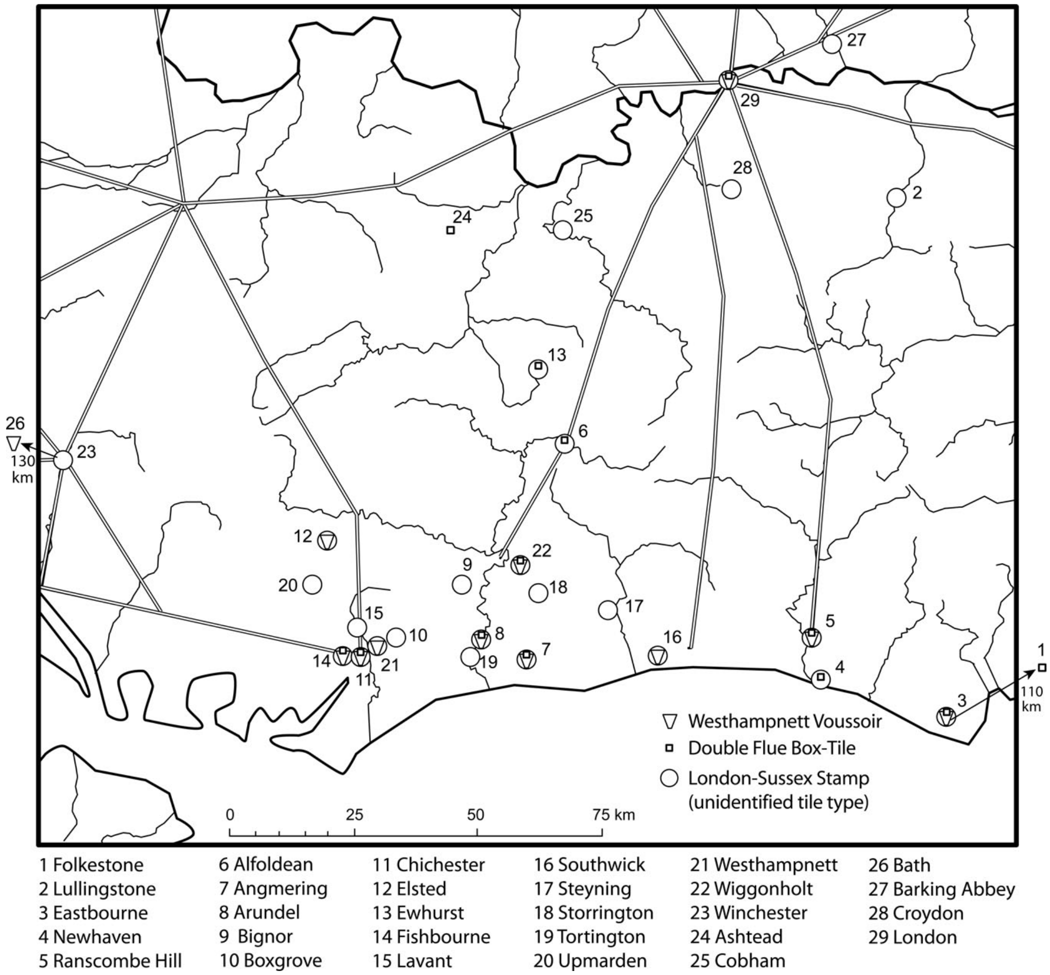
89. Reconstruction of a *caldarium* with *tegulae mammatae* on both walls and vaults (modeled on examples from Pompeii and Herculaneum).

(c. 60–65 CE), the Huggin Hill baths in London (c. 70 CE), and the fortress baths at Caerleon (c. 75 CE).[11] The introduction of the earliest hollow voussoirs followed soon thereafter, probably in the mid to late 70s under Vespasian.

The first generation of hollow voussoirs can be identified by the roller stamps that occur on many of them and by the fabric associated with the group of dies used. The early voussoirs also have three other characteristics that are different from later ones: (1) semicircular vents on the sides just above the bottom (intrados) surface, (2) thick walls (2.5–3.0 cm), and (3) rounded interior corners that served as reinforcement. In general they are much heavier, sturdier, and better made than later examples. This early type has been dubbed the *Westhampnett voussoir*

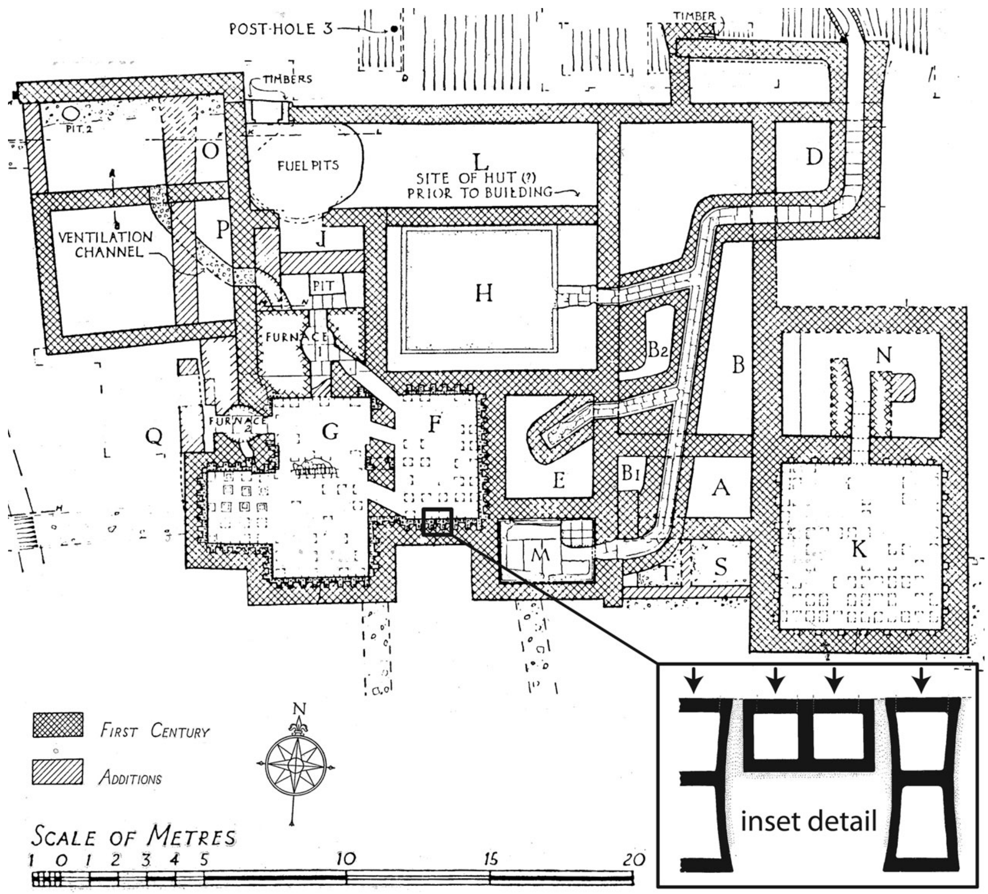


90. Two tiles from the workshop using the London-Sussex Group dies. A: Westhampnett voussoir from the church in Westhampnett, England. Die 21 is on the face and die 22 is on the bottom surface (not visible here). B: Double flue box-tile from Angmering bath (Barbican House, Lewes, Accession #1953.16). Die 19 is on the short side and die 21 on the upper face.



91. Distribution map of tiles with stamps of the London-Sussex Group (Westhampnett voussoirs and double box-tiles indicated). Note that the tiles from Ashtead, Bath, and Folkstone do not bear stamps of the London-Sussex Group.

because a number of them were discovered reused in the Saxon parts of the church in Westhampnett just outside Chichester in Sussex.[12] They appear to have been part of a modular system of terracotta heating elements because they almost always occur together with an unusual form of double flue box-tile that shares the same fabric, the same group of dies (called the London-Sussex Group), and the same sturdy construction details (Fig. 90A–B).[13] Fabric analysis shows that the workshop specialized in tiles for bath buildings.[14] The distribution of the dies associated with this workshop covers an area from London southward through Sussex (Fig. 91). The fabric is quite distinct from other fabrics found in London, so the builders were clearly not based there. The concentration of examples around Chichester suggests that the tiles were probably made nearby, though no kiln has been found that can be associated with them. The robust construction of the box-tiles suggests that they were meant to play a structural role in the building, unlike earlier box-tiles that were attached to the wall with nails. Therefore, this workshop may represent a type of design/build firm that made both the components and the building itself.[15] The datable findspots



92. Angmering bath building (last quarter of first century CE). L. Scott's excavation plan (Littlehampton Museum). Inset shows detail from Scott 1938: fig. 11 (arrows indicate cutouts on front face of wall).

of the stamped tiles indicate that this workshop was active during the Flavian period in the last quarter of the first century CE.[16]

None of the Westhampnett voussoirs has been found in situ, but at Angmering, about 20 km east of Chichester, the double flue box-tiles are preserved in their original positions (albeit backfilled now) and provide information for how the whole heating system worked. The site was excavated in the 1930s, and a plan and photographs were made at the time and published in an interim report by L. Scott.[17] In addition, one of the double flue box-tiles was salvaged from the site and survives intact at Barbican House at Lewes (Fig. 90B); a fragment of a Westhampnett hollow voussoir also survives in the British Museum.[18]

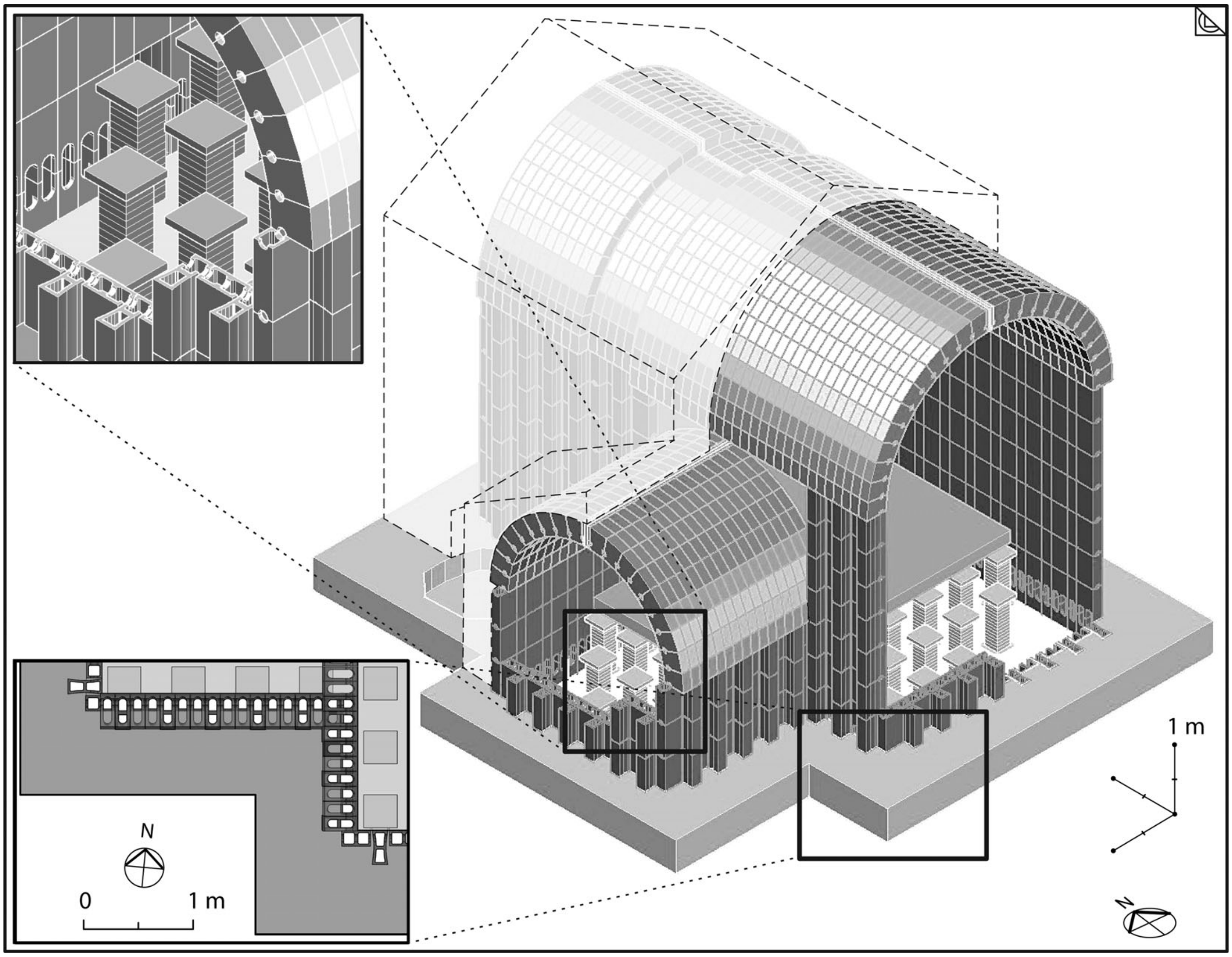
The box-tiles were found in situ in the walls of both the *caldarium* G (3.4 m span) and *tepidarium* F (2.8 m span) of the Angmering bath (Figs. 92, 93). Some of the tiles are very unusual in that the sides bow inward in an hourglass shape, with the central division occurring at the narrow point. They were set perpendicularly into the wall, alternating with the more typical rectangular double flue box-tiles set parallel to the wall (Fig. 92 inset). They appear to have been put in place as the wall was being built, as shown by the mortared rubble built directly up against the tiles without any facing. This is quite a different approach from the typical method of bath construction where a faced wall was built first and then the box-tiles were attached with iron cramps.

93. Angmering bath building (last quarter of first century CE). Excavation photograph of the projecting wing of the *caldarium* (room G). Arrow indicates bowed double box-tile (photo: Littlehampton Museum).

None of the bowed tiles was salvaged from the site, but the photograph shows that they were built in the same sturdy manner as the others with the rounded reinforced corners.

Scott's drawing (Fig. 92 inset) indicates that the bowed tiles were somewhat wider and longer than the rectangular ones, which as E. Black points out would have allowed the Westhampnett voussoirs to fit above them. However, he also questioned whether the voussoirs were in fact used in these rooms because the bowed tiles do not align on opposite walls.[19] Nevertheless, given that the Westhampnett voussoirs almost always occur together with the double flue box-tiles at other sites (Fig. 91), the two types seem to have been intended to be used together. In reality, if the vault was made up entirely of continuous bands of hollow voussoir arches set side by side (Fig. 94), the fact that the bowed tiles do not align on either side of the room is less problematic because each voussoir would receive some heat from the flue below it with every third arch receiving more heat than its neighbors (Fig. 94 lower inset). Moreover, the semicircular cutouts on the Westhampnett voussoirs were designed to form circular vents when the voussoirs were put together, and the fact that the resulting vents aligned in each arch indicates that the air was intended to circulate. In Figure 94, I reconstruct a hypothetical arrangement for the heating system.[20]

The Westhampnett voussoirs have been found in the baths of a series of elegant villas along the south coast of Britain, as well as in urban contexts at Chichester, Winchester, and at twenty-two sites in

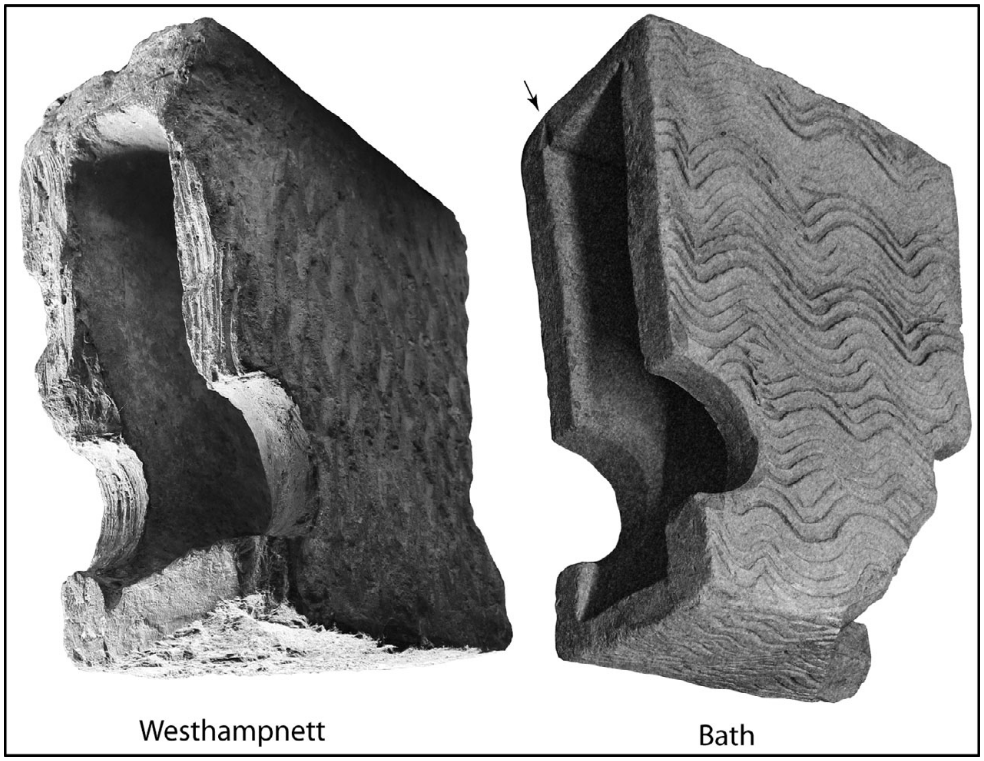


94. Angmering bath building (last quarter of first century CE). Author's reconstruction of the *caldarium* illustrating how the hollow tiles would have been configured. In the lower inset, note that the white areas within the tiles are where the air would have been able to enter into the vault tiles.

London. Once introduced, the technique clearly became very popular, but it remained in the hands of this one workshop employing the London-Sussex Group roller stamps. In spite of the militarization of the province, there are no examples known from military contexts. The fact that its use was concentrated mainly in the modern region of Sussex suggests that it was an invention by local tile makers who specialized in bath buildings and catered to the local elite, many of whom may have belonged to the Roman-friendly Regni tribe that ruled this area during the first century. The tile makers then expanded to supply London during its period of intense urbanization under the Flavians.

THE NEXT GENERATION

As the technique grew in popularity the Westhampnett voussoirs were soon replaced by the more typical hollow voussoir with thinner walls and vents (when they existed) cut out of the center of the faces, rather than the distinctive semicircular cutouts on the side. However, there is one example that appears to represent a transitional phase in which the original idea



95. Comparison of Westhampnett hollow voussoir (left) and the similar type from Bath (right). Note the curved interior of the Westhampnett voussoir resulting in thicker corners. Compare the Westhampnett-type at Bath with rectilinear corners, thinner walls, and crack (arrow) where the slab was joined around the mold.

of the Westhampnett voussoir was adopted by a different workshop and applied outside the distribution area of the Sussex builders. To the west at Bath, three whole Westhampnett-type voussoirs have been found along with fragments of others, none of which is in the fabric of the London-Sussex Group. One of the three is now at the Colchester Museum, but the other two remain at Bath.[21] All three are the same height (34 cm) and would have fit a vault with a span of c. 3 m. They all appear to have been made in the same workshop because they display wavy combing with the same 5.65 cm wide, seven-tooth comb, and no roller stamping. The other fragments are different – they have a height of 36 cm and cross marking made with an eleven-tooth comb.[22] These tiles from Bath still have thicker walls than the later ones, but they lack the characteristic rounded and thickened corners of the first generation (Fig. 95). Without further information on their context, it is difficult to speculate where or when they were employed, but because they appear to be imitations of those made by the Sussex workshop, a date in the late first or early second century seems likely.[23]

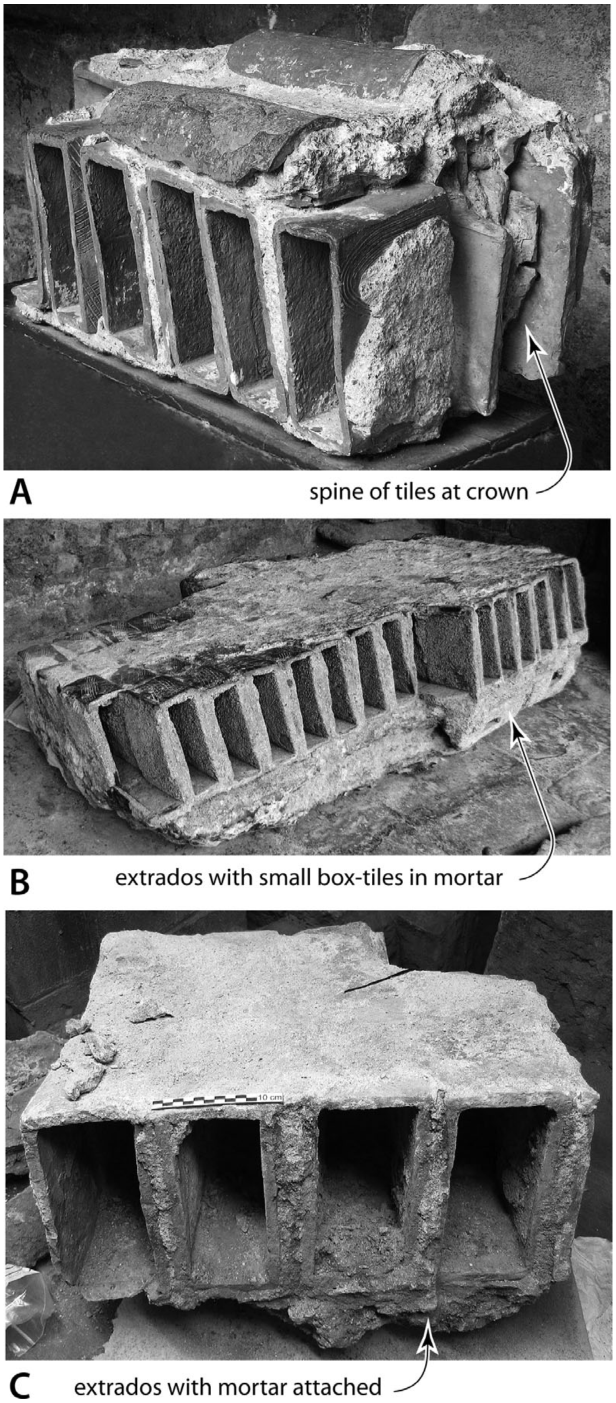
During the first quarter of the second century a variety of other lighter voussoirs made by a number of workshops began to appear; some were roller stamped, but the majority were combed. The area of densest use shifted from Sussex eastward to Kent. As in the earlier period, precise dating is often difficult, but a clear increase in the use of the voussoirs occurred during the Hadrianic period, possibly stimulated by the emperor's visit to the province in 122 CE.[24] This trend is attested both by datable bath structures and new roller stamps associated specifically with the hollow voussoirs. The increased use of the voussoirs appears to be part of the expansion of box-tile manufacture in general (along with bath building), which in turn was due to both increased urbanization and the villa construction in the surrounding countryside that came with it.

PURPOSE

Two purposes most often attributed to the hollow voussoirs are as heating elements and as structural elements to lighten the vault and reduce its lateral thrust. The analysis of the Westhampnett voussoirs demonstrates clearly that their original purpose was as part of the heating system. All the vaults were quite small, usually spanning three to five meters, so the lateral thrust would not have been a great issue (see Case Study 1, Chapter 8). In contrast, heating the vaults could have had an impact on both comfort level and the amount of fuel burned. As shown by the analysis of the experimental bath in Sardis, adding box-tiles to the walls reduced the fuel consumption by 20 percent in comparison to a bath with a hypocaust alone. This is explained because "by increasing the area of heated surface (radiant energy) within the room it enabled the system to operate at a lower surface temperature with greater efficiency and less energy consumption."[25] The application of this principle to the ceiling as well would further increase the amount of radiant energy flowing into the room; however, the potential benefits of the system were only effective as long as the external surface of the hollow voussoirs had some type of thermal insulation so that the vault's radiant energy was not lost to the environment. So, for example, if the voussoirs were left bare on the top surface and a wooden roof were placed above the vault, much of the radiant heat would be lost to the attic space.[26]

We have very little evidence for how the vaults were covered on the exterior. There are only two examples – at Canterbury and at Bath – for which there is good documentation; both had a layer of mortar along the extrados. At the public baths at Canterbury, the fallen vault of the *laconicum* (9.2 m span) was excavated in situ where it fell. The stratigraphy indicates that a 7 cm layer of crushed terracotta mortar was still adhered to many of the hollow voussoirs, many of which were found in situ still aligned in ribs. This layer was sealed by "loose tile and mortar rubble in dark soil."[27] Despite the occurrence of the vault over a heated room, the voussoirs were reused, and there is no evidence to verify if the vault was connected to the heating system. At the Sanctuary of Sulis Minerva at Bath, two chunks of fallen hollow voussoir vaulting are on display in the Great Bath (Fig. 96A–B, WebFigs. 28–29) and others are in the storeroom (Fig. 96C, WebFig. 30). All show traces of crushed terracotta mortar on the extrados. It is not clear to precisely which vault each belonged, but those in Figure 96A–B are 31 cm tall – the same size as those reported in the nineteenth-century excavations of the Great Bath[28] – so they could have come from the (nonheated) main vault (10.5 m span). The findspot of the third chunk (Fig. 96C, WebFig. 30) is not recorded, so whether it was heated is not known. However, a drawing from 1869 of the west *tepidarium* (5.5 m span) shows a section of the fallen vault of hollow voussoirs (just over 30 cm tall) with mortar along the extrados. This room preserves some box-tiles along its south wall, so the hollow voussoirs could have been, and likely were, connected to the heating system in this room.[29] The drawing also confirms that the hollow voussoirs were used not only for the very large vaults of the Great Bath and the Sacred Spring (see Chapter 8) but also for other rooms in the complex.

An additional reason to think that the hollow voussoir vaults would have been covered by a mortar coating of some type is demonstrated by the problems encountered in the hollow voussoir vault at the reconstructed bath at Xanten, where a wooden roof



96. Chunks of hollow voussoir vaulting from Bath, England with crushed terracotta mortar between the tiles and covering the extrados. A: Piece from crown of a vault with spine made of pieces of *tegulae*. Voussoirs are 31 cm tall. B: Piece lying with intrados up. The extrados has long thin rectangular box-tiles attached with mortar. Voussoirs are 31 cm tall. Box-tile has interior length of

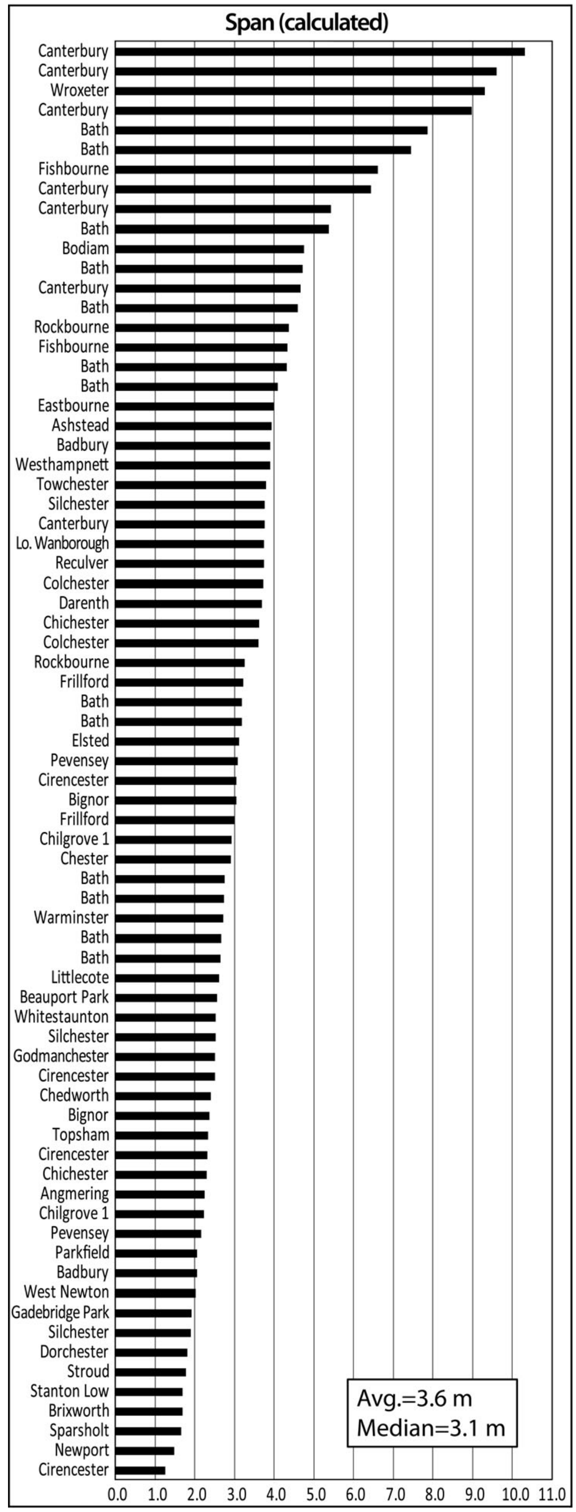
was adopted. The intrados of the vault was coated with an internal layer of plaster, but the extrados was left bare. As a result, the vault heated up and expanded much more quickly than the wall box-tiles, which were backed by the masonry wall. The walls absorbed the heat and contained the expansion at the side, so the vault had to expand upward, causing shear stresses where the crown of the vault met the back wall and resulting in cracks both between the back wall and the vault and along the crown of the vault. As P. Kienzle notes in his report on the interventions at Xanten, a layer of mortar along the extrados would have helped absorb the heat and allowed for a more consistent expansion throughout the structure.[30] For the hollow voussoirs to have been effective both thermally and structurally, they would have required a mortar coating along the extrados at the very least. Some other finds suggest that the curved extrados of vaults was sometimes tiled. P. Warry has documented convex *tegulae* at forty-four sites in Britain. Thirteen of these sites also had hollow voussoirs, but whether the two types of tiles came from the same roof is not clear.[31] Other evidence indicates that concrete vaults in Britain sometimes took a gabled form. A fallen vault of a room from the bath at Bewcastle retained both its curved intrados and its slanting extrados.[32] Without further evidence from the hollow voussoir vaults themselves, it is impossible to establish a pattern in the roofing of these structures, but a mortar or concrete covering, either curved or gabled, would clearly not be unusual.

Results of the heat analysis from the experimental bath at Sardis showed that the box-tile wall heating system could operate without a flue because a convection system acted within the wall so that the air circulated on its own. Though not specified

96 (*continued*) 13.5 cm on wide side and is 44 cm long. C: Piece from York Street storeroom with intrados up and crushed terracotta mortar still attached to extrados. Voussoirs are 22.5 cm tall. (Color images: WebFigs. 28–30).

in the report, this finding presumably relates to the operation *after* the initial heating of the bath, which would have benefited from a flue to pull the heat through the building and set up the convection system. Twelve percent of heat loss at Sardis came from expulsion of gasses through the flue, so the ability to close the flue could increase efficiency. The vents in the Westhampnett voussoirs would have allowed this type of convection system to be extended into the vault. Indeed, in the reconstruction of the *caldarium* at Angmering in Figure 94, more hot air was delivered through every third arch via the bowed double flue box-tile; this configuration could have been an attempt to promote convection within the vault by varying the amount of heat in the arches.

The fact that some hollow voussoirs do not have vents has raised the question as to whether they were intended mainly as structural devices to lighten the vault, rather than as part of the heating system.[33] However, in most cases, we do not have a large enough sample to know if all the voussoirs were vented or not. The only voussoirs from heated rooms that were found either in situ or in great numbers come from the large vault (9.2 m span) over the fourth-century *laconicum* of the public baths at Canterbury and the very small vault (2.3 m span) over the *caldarium* pool of a bath at Beauport Park. Both had substantial numbers of vented voussoirs, but many of those at Canterbury were reused.[34] The examples without vents rarely occur in enough numbers to determine whether they were combined with vented ones or not. Combining vented and unvented tiles could have been a means of controlling the circulation of gasses within the vault. For the most part, vaults built with the hollow voussoirs were quite small and would not have provided great structural benefit. For example, applying the formula for determining spans (Fig. 86) to seventy-three voussoirs for which measurements are available yields an average span of 3.6 m and a median of 3.1 m (Fig. 97, WebCat. 6-B).



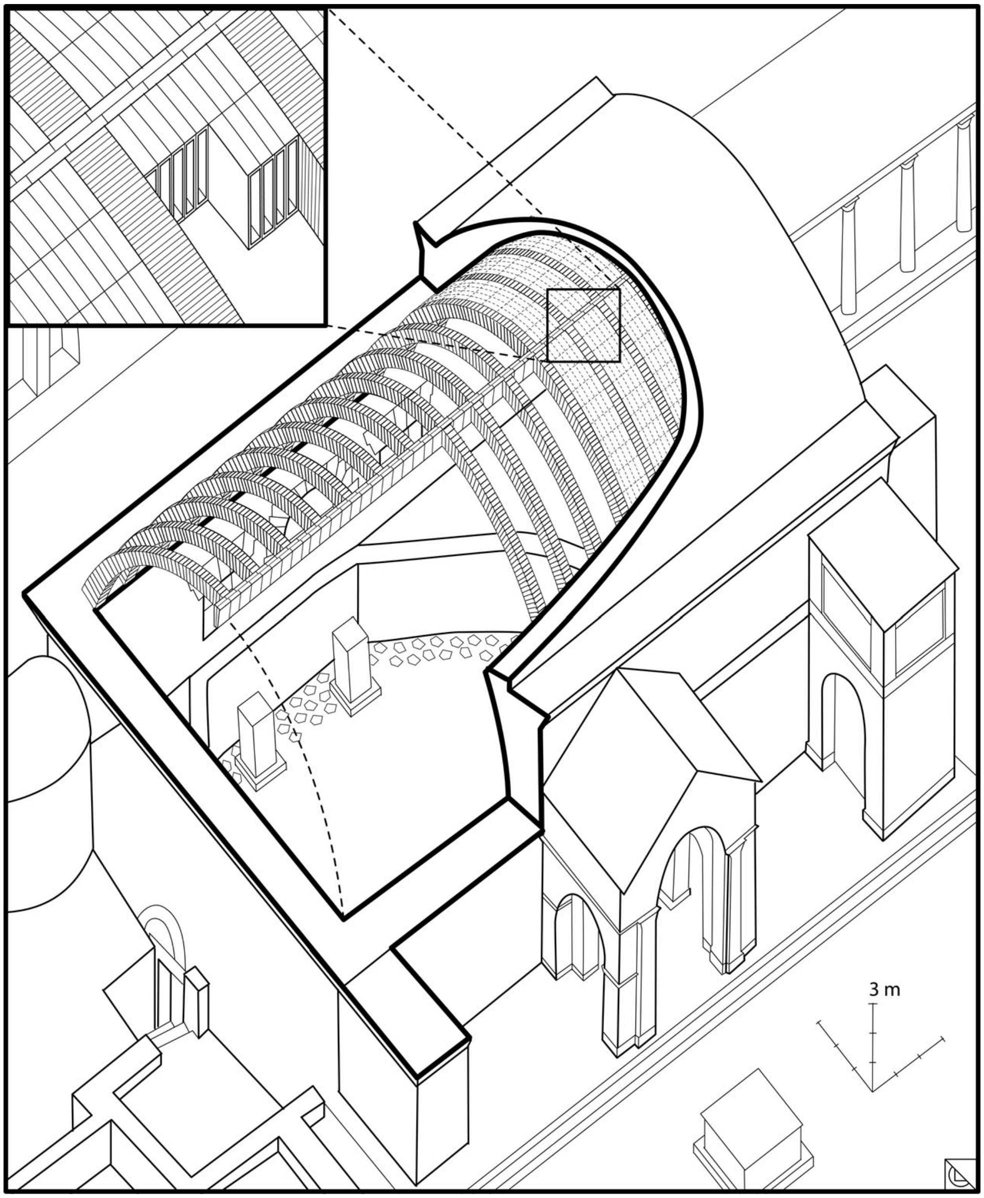
97. Chart of vault spans calculated from extant hollow voussoirs using the formula in Fig. 86.

As discussed at the beginning of the chapter, this formula can yield substantial variations even with small inaccuracies in measurements; however, if we look at the twenty-nine room sizes from preserved room plans that can reasonably be associated with the voussoirs, the results are similar, with an average span of 4.2 m and a median of 3.0 m (WebCat. 6-C). As discussed further in Chapter 8, creating lighter vaults is only beneficial once the vault reaches a span of around 6 m, so fewer than 15 percent of the vaults from either list would have derived any structural benefit from the use of the hollow voussoirs.

Only three buildings have hollow voussoir vaults with sizes that go significantly beyond the averages: the original *caldarium* (9.5 m) and the rebuilt *laconicum* (9.2 m) at the public baths at Canterbury, the *frigidarium* (9.6 m) of the public baths at Wroxeter, and the Great Bath (10.5 m) and the Sacred Spring enclosure (13.6 m) of the Sanctuary of Sulis Minerva at Bath. Significantly, in only one building (Canterbury) do the vaults occur in heated rooms, though we do not know if they were connected to the wall heating system. If the voussoirs of the *caldarium* at Canterbury are coeval with the walls (first quarter of second century CE), they are the earliest of the large-scale vaults attempted. Unfortunately, there are no roller-stamped voussoirs published from this vault to confirm their date. Chronologically the next example comes from the Wroxeter public baths (mid-second century CE), where the voussoirs were found in the area of the *frigidarium*. The measurements of the voussoirs taken from the excavation drawings yield a span of 9.3 m,[35] so they can reasonably be associated with that room, which measures 9.6 m. The vault covering the Sacred Spring at Bath, which is usually dated to the late second/early third century, covers naturally heated springwater, so there is no hypocaust to provide heat for the voussoirs. It is the largest (13.6 m) in Britain (within the northern provinces it is second only to the *caldarium* of the Imperial Thermae at Trier [19 m]) (WebCat. 1). Its voussoirs are also the largest known examples (44 cm high), which emphasizes their structural nature. Fortunately it is also one of the best-documented examples because it fell into the Sacred Spring and was preserved until its excavation in 1985, so it can be reconstructed with a certain degree of accuracy (Fig. 98). The latest example is the early fourth-century *laconicum* added to the public bath at Canterbury, which employed at least some reused voussoirs (die 32).[36] All of these vaults are so large that a structural function can be assumed, particularly in the cases where they are clearly not connected to a heating system (Bath, Wroxeter). The structural efficacy of the examples from Bath is explored further in Chapter 8.

The preceding discussions indicate that hollow voussoirs began as part of the heating system of baths and only later were adapted to be used as a structural element for very large vaults. Thus originally the purpose was evidently to increase the comfort level of the bath and possibly its fuel efficiency. Some insight into the latter issue is provided by the experimental baths at both Sardis and Xanten. The Sardis heat calculations showed that the greatest inefficiency of the whole system resulted from burning off the moisture from the wood used as fuel; combustion accounted for 45 percent of heat loss and burning off the moisture for an additional 34 percent.[37] At Xanten, there were tangible ill effects from the burning of wood with high moisture content; it caused the sulfur dioxide to precipitate inside the box-tiles and penetrate the terracotta and plaster to discolor the interior decoration. It also caused a tar-like soot to accumulate in the hypocaust, which after a time became brittle and broke off to fill the hypocaust.[38]

The type of fuel used clearly affected the operation of baths, so one question is whether there was any attempt to use efficient and clean-burning fuels. An inscription from Misenum specifies hardwood (*ligni duri*) as fuel for heating the baths.[39] As fuel,



98. Author's reconstruction of the Sacred Spring of the Sanctuary of Sulis Minerva at Bath, England (based on Cunliffe and Davenport 1985: figs. 31, 115).

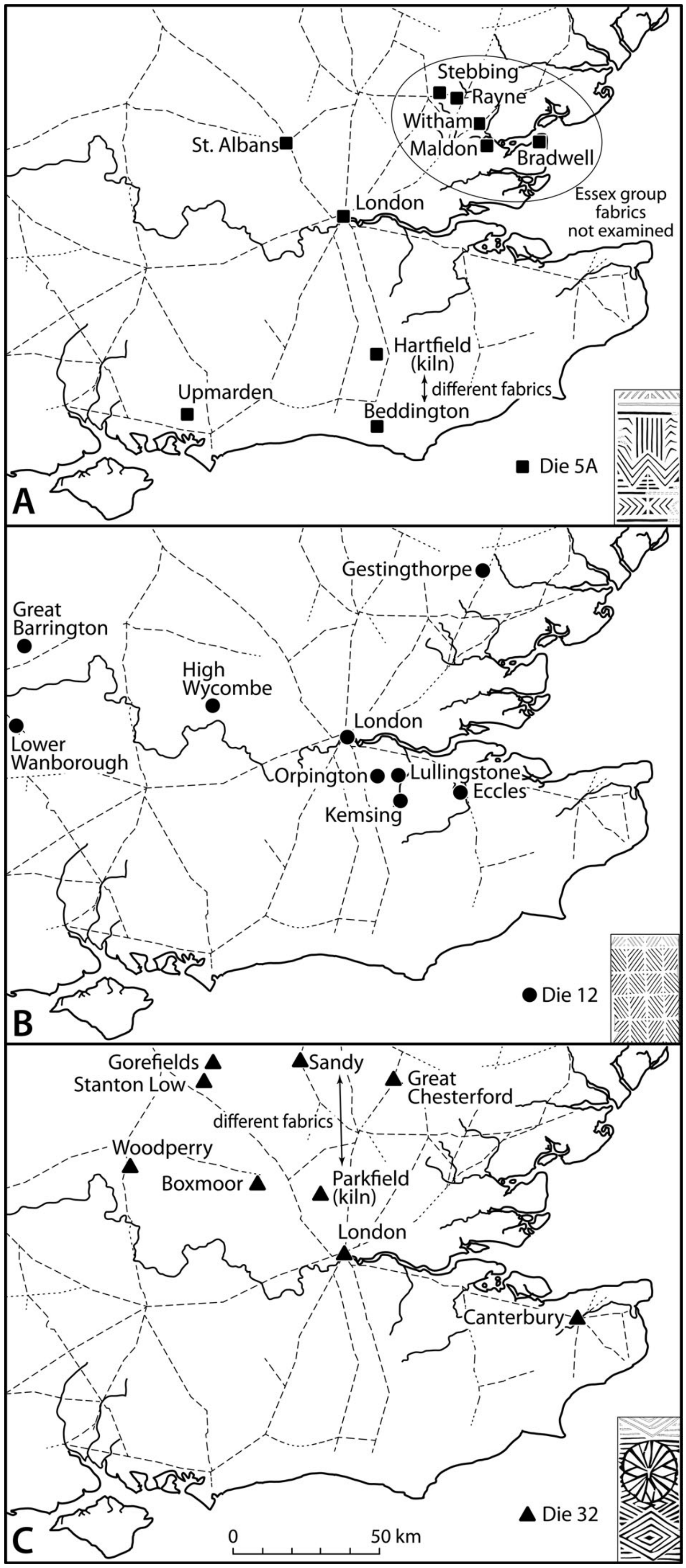
hardwoods have the advantages of providing greater heat potential per volume, containing less resin (i.e. cleaner burning), and burning for longer periods than soft woods. However, excavated *praefurnia* suggest that soft woods were often used. At the villa baths of La Vautubière (third century CE) at Coudoux in Narbonensis, the primary types were olive, Aleppo pine, and holm oak. At Bath 1 at Labitolosa in Spain, excavation of the *praefurnia* revealed that the fuel from the early period of operation (first century CE) consisted largely of pine, whereas the second-century strata were made up mainly of holm oak. These findings are consistent with the 3–4 cm layer of soot deposited. In olive-growing regions, olive wood and olive pressings were used, as at La Vautubière, the phase 2 baths of the villa at Saint-Michel at La Garde in Narbonensis, and the Baths of Julia Memmia at Bulla Regia in Africa Proconsularis.[40] The most efficient and clean-burning material is charcoal because moisture and contaminants are burned off before use. The report from the Angmering bath noted a large proportion of wood charcoal in the *praefurnia*, but it is unclear if this represented charcoal used for fuel or the carbonized remains of wood fuel (wood type not reported).[41] Without further reports on the fuel from *praefurnia* of baths employing the hollow voussoirs, it is difficult to know if there was an attempt to run these baths more cleanly and efficiently than baths without heated vaults.[42] Nevertheless, from the more recent excavations in France, Spain, and Tunisia, we can see that clean-burning efficiency in general may have been more desirable than practicable.

PRODUCTION MODES AND DIFFUSION

As we saw with the Westhampnett voussoirs, the roller stamps are very useful for tracing workshops, and they continued to be used into the second century on both box-tiles and hollow voussoirs. The information from roller stamps, archaeometric analysis of tiles, and excavation of kiln sites, has demonstrated that the organization of the manufacture and distribution of both box-tiles and hollow voussoirs increased in complexity during the first half of the second century. Instead of a single firm making and distributing both box-tiles and hollow voussoirs from a central location (as indicated by the same fabric used for the London-Sussex Group), the evidence suggests that a variety of distribution methods were in use at the same time and often in the same areas.

A kiln excavated at Hartfield in East Sussex provides useful information regarding the production of the voussoirs and the practice of roller stamping. Both box-tiles and hollow voussoirs were produced at the kiln, the date of which was determined by magnetometry to have been in the period 100–130 CE (68 percent accuracy). The box-tiles found at the site were mainly combed (93 percent by weight) with a minor proportion roller stamped with die 5A (4 percent by weight); thus, the roller-stamped ones were produced together with combed ones, but at a much-reduced rate. Hollow voussoirs were also found, but none was roller stamped. Of the box-tile and hollow voussoirs found, the latter accounted for only 15 percent.[43] Analysis of tile fabrics from other kilns and villa sites in the area demonstrated that products from the Hartfield kiln were distributed within about a 35 km radius.[44] However, one box-tile with die 5A found at Beddingham, about 25 km south of the kiln, was made of a different fabric and suggests an itinerant tile maker who took his die with him (Fig. 99A). This is supported by the fact that the greatest cluster of box-tiles with die 5A occurs in Essex about 85 km north of the Hartfield kiln; those box-tiles were likely produced in a different kiln closer to these sites (fabric not examined). The Hartfield kiln thus demonstrates that box-tiles and hollow voussoirs were made together, that the tiles were distributed widely, and that itinerant workers were associated with the dies on the box-tiles.

The hollow voussoirs are more difficult to track than the box-tiles because fewer roller stamps are associated with them, but evidence suggests a similar mode of distribution. Hollow voussoirs with die 12 were found at a villa at Eccles in Kent and were made of local clay. Other examples of die 12 were found on tiles of a different fabric 150 km to the west at Lower Wanborough in Wiltshire and Great Barrington in Gloustershire, thus suggesting a tile maker who traveled (Fig. 99B).[45] Die 32, which only occurs on hollow voussoirs, was found at the kiln excavation at Parkfield (Potter's Bar) in Hertfordshire.[46] The distribution of this roller stamp ranges from 20 to 65 km from the kiln, with no examples known in



99. Distribution maps of tiles bearing roller stamps. Dashed lines are roads (dotted where path is uncertain) (after Betts et al. 1994: figs. 15,18, and 19). A: Die 5A (on box-tiles). The finds of the same die in different fabrics at Hartfield and Beddington suggest an itinerant tile maker. The fabric of the Essex group has not been tested, but the clustering at such a distance from the kiln at Hartfield also suggests itinerant tile makers. B: Die 12 (found on a hollow voussoir at Eccles). C: Die 32 (exclusively on hollow voussoirs). The finds of the same die in different fabrics at the Parkfield kiln and at Sandy also suggest a tile maker who traveled.

the vicinity of the kiln itself (Fig. 99C).[47] In at least one case at Sandy in Bedfordshire (45 km away), the fabric is different from the others and again suggests that this tile maker traveled with his die. Examples were also found 150 km away at Canterbury in Kent, and at least one was found in the collapsed roof of the *laconicum* of the public baths, discussed earlier, which is among the four largest known.[48] The tile must have been reused because this room was added in the fourth century, but even so the voussoir would have originally covered a similarly large room.

The only dies (31/59) to incorporate the full name of the maker, Cabriabanus, occur on voussoirs concentrated in Kent (Fig. 87). Cabriabanus, whose name is Celtic, evidently took particular pride in his work, possibly because making voussoirs was a more demanding task than making other types of tiles since they had to be crafted to fit a given span. The die is crudely cut with some letters backward and upside down and others transposed, but it clearly reads "*parietalem Cabriabanus farbicavi*" (Fig. 88, die 31), which translates to "I Cabriabanus manufactured (this) wall-tile." Given that the roller stamps occur on voussoirs (*cuneati*), the use of *parietalem* is difficult to explain. One suggestion is that *fabricavi* (albeit misspelled) was used instead of the typical *feci* to fill the space taken up by the maker's name,[49] so perhaps a similar rationale applies to the misnaming of the tile type.

With the exception of one example from Bishopsgate in London, Cabriabanus's tiles have all been found at two villas in Kent, at Plaxtol and at a site 18 km north at Darenth. At Plaxtol, the kiln (1.5 × 2.5 m) that likely fired them has been discovered. Magnetometry has given a date of operation of some time between 120–165 CE (95 percent accuracy). The same fabric was used for hollow voussoirs bearing a different roller stamp (die 73 with geometric pattern) found at two other villas in Kent (Lullingstone, Chalk) and also at Bishopsgate London. A third roller stamp, die 127, also occurring on a voussoir in a very similar fabric, was found at the Guildhall excavations in London.[50] Thus there may have been more than one tile maker, possibly using the same kiln, supplying villas in both Kent and sites in London. This mode of manufacture, with multiple potters sharing a kiln, is documented in both North Africa and Gaul.[51]

Some of the excavated kilns appear to have been used for a very brief period and then abandoned, such as the ones in Hartfield and Plaxtol. However, another set of kilns excavated at Minety in Wiltshire (the most extensive tile works in Britain) appear to have operated from the Flavian period through the third century. During the Hadrianic period, this tilery put out products associated with four different roller stamps (25, 53, 56, and 92), all of which occur on the same fabric.[52] Only die 56 from Bath can be associated with a hollow voussoir, though other voussoir fragments with this roller stamp were found in one of the Minety kilns. All four roller stamps mainly appear within 10 to 45 km of the site. Thus, this expansive and long-lived tilery does not appear to have been as specialized as the ones discussed earlier,[53] but it is located far to the west where less demand made a central manufactory more practical.

These few examples of kiln excavations demonstrate that during the second century the production of heating tiles for baths appears to have grown more complex than what we saw with the Westhampnett voussoirs around Chichester in the last quarter of the first century. A greater degree of specialization is represented by the separation between the manufacture of box-tiles and that of hollow voussoirs. Box-tiles could have been mass produced to a certain extent and acquired from different suppliers. Hollow voussoirs, in contrast, were a made-to-order item; they had to be constructed to fit a particular vault, which could be one reason for the specialization. The tile makers responsible for the voussoirs also needed to have direct contact with the bath builders. The supply of the specially made vaulting tiles therefore depended on a system of special orders, a good transport network (both river and road), and occasional itinerant tile makers.

In sum, based on the evidence assembled by of the Relief-Pattern Tile Research Group,[54] the following three observations can be made:

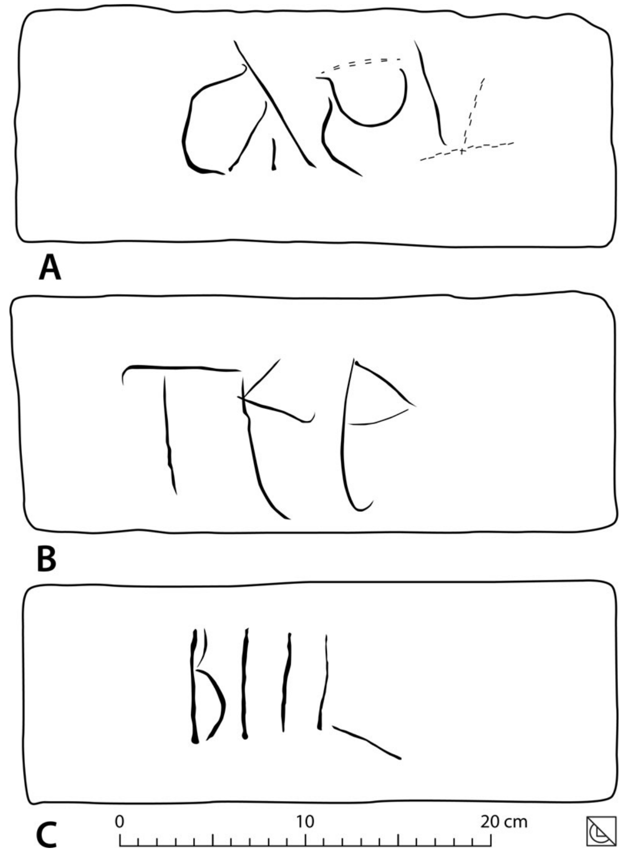
1) The voussoirs were sometimes made by specialist workers, as demonstrated by some roller stamps being used only on hollow voussoirs (dies 30, 31, 32, 59).
2) The tile makers (of both box-tiles and hollow voussoirs) were sometimes itinerant, as demonstrated by the same roller stamp being used on different fabric types (e.g., dies 5A & 32).
3) Both box-tiles and hollow voussoirs with roller stamps could have a fairly wide geographical distribution, which was dependent on a good transportation network.

The latest datable roller stamp used on a hollow voussoir is die 30 (Fig. 88) from the public baths at Leicester dated to around 155–160 CE.[55] The practice of marking tiles with the roller stamps was less common in the second half of the century and seems to have ceased altogether by the end of the century[56]; with it went one means of dating the tiles. Many of the examples listed in the catalogue (Web-Cat. 6-A) were not found in their original context. In urban areas, dating is particularly problematic because broken tiles were often moved between sites to be used as fill. After the second century, new construction slowed in Roman Britain, tile production decreased, and there was a great deal of reuse of tile, including hollow voussoirs. There may have even been depots for redistribution.[57] However, during the fourth century there was a renaissance of both public and villa construction and renovation, and the hollow voussoirs again appear (e.g., Bignor, Binchester, Chedworth, Chilgrove 1, and Canterbury). Were these late structures reusing earlier voussoirs, or was manufacturing renewed? Without the roller stamps, it is difficult to know for sure. One hint that at least some new voussoirs were manufactured in the fourth century comes from an excavated kiln at Heighington in Lincolnshire where hollow voussoirs were found among the wasters. That fourth-century pottery was mixed in the destruction debris implies that the kiln was active up until this period.[58] However, hollow voussoir fragments with second-century roller stamps are often found in late contexts, such as the voussoir with die 32 used in the *laconicum* added to the public baths at Canterbury in the early fourth century.[59] Thus some combination of newly produced and reused tiles seems to have occurred during this late period of reinvigorated building activity.

Finally, two examples of hollow voussoirs have been found outside Britain, at Xanten in Germany and Bliesbruck in France (Fig. 87). The one at Xanten (mid-second century CE) (home of the Legio XXX Ulpia Victrix) has already been discussed. The presence of a legionary base suggests a possible link via military personnel transferred from Britain. In contrast, the other example occurs at a bath (first half of third century CE) in Bliesbruck, France, on the German border about 275 km south of Xanten,[60] where there is no evidence to suggest military involvement. Additional evidence supporting a civilian source for the idea comes from a group of roller-stamped tiles found in a 45 km radius around Dieberg (just south of Frankfurt) halfway between Xanten and Bliesbruck. The roller stamps, the only examples known outside Britain, occur on flat tiles rather than box-tiles, but like the box-tiles they were used to clad walls, usually of heated rooms in baths, with the roller patterns intended to create a purchase for plaster. They can be dated to the second half of the second century CE. D. Baatz notes that, of the ten sites in which the tiles have been found, only one is associated with the military and postulates a civilian origin emanating from Dieberg.[61] Taken together, the existence of the hollow voussoirs and the roller-stamped tiles in this area of northern Europe may suggest that the technology transfer is due to itinerant tile makers relocating from Britain across the Channel to northern France/Germany. In any case, these finds highlight the close connection between both sides of the Channel.

CONCLUSIONS

The earliest uses of the Westhampnett voussoirs appear to have been in elegantly appointed private baths that were part of the vanguard of the emerging villa scene in the Regni territory of southern Britain. The villas represent what B. Cunliffe has called "a precocious development of *romanitas*."[62] The Regni were known for being particularly pro-Roman both before and after the Roman conquest in 43 CE[63] and had already begun to enjoy the amenities of Roman culture even before the Roman invasion, as attested by finds of imported wine amphoras and terra sigillata fine ware from the Augustan period.[64] One of the most important patrons in the area must have been the owner of Fishbourne palace, where tiles, including Westhampnett voussoirs, stamped with the London-Sussex Group dies were found. The perennial question surrounding Fishbourne is whether the first owner was the enigmatic king of the Regni, Togidubnus, who is known from both Tacitus and an inscription in Chichester.[65] Without getting into this vexed question here, I simply point out that, regardless of the identity of the owner, the earliest hollow voussoirs were employed in the most elaborate palace in Roman Britain. Unlike some other parts of Britain, this area was largely unfortified and controlled by the local elite.[66] Thus the economic impetus for the development of the hollow voussoirs may well lie with the wealthy landowners in Regni territory.



100. Grafitti on the top sides of Westhampnett voussoirs. A–B: Examples built into wall of Westhampnett Church (*RIB* II.5, 2491.84; *RIB* II.5, 2491.126; Tomlin 2012: 421). C: Example found reused in a fourth-century CE bath at Elsted (Batten Hanger) (Tomlin 2012: 411).

The graffiti on the topsides of three of the Westhampnett voussoirs provide some idea of the people involved in making the original voussoirs. Two are built into the church at Westhampnett. One has been deciphered as CALVI, which reads "of Calvus," indicating that the maker of the tile had a typical Latin name (Fig. 100A).[67] The other is interpreted as T F P, which are probably the initials of a *tria nomina*: The sequence of T F suggests T(itus) F(lavius), which would signify a person who had recently become a citizen under a Flavian emperor or who belonged to a recently enfranchised family (Fig. 100B).[68] Three other identical graffiti were found reused in a fourth-century villa bath at Elsted (Batten Hanger) and have the letters BIIL (Fig. 100C). The two vertical marks after the B are a form of E that remained common in Gaul after it had gone out of regular use in Italy (except in wax tablet orthography).[69] The graffito would then read "Bel" and is presumably the abbreviation of the maker's name, given that it occurs on three different voussoirs found together. The prefix Bel- is common in many Celtic names in both Britain and Gaul: Belinatepus, Bellatorix, Bellognatus, and Bellicus, among others.[70] The evidence from the orthography and the name suggests that this maker had Celtic roots and was either a local Briton or a Gallic immigrant. If from Gaul, he could represent one of the many craftsmen who migrated to Britain in the wake of the invasion, arriving with expertise in terracotta production techniques. Elsewhere I have suggested that the idea for the roller stamps on tiles could have come from their use on Gallic pottery, albeit at a much smaller size.[71] Such pottery was not commonly exported to or produced in Britain itself, though that was not unknown – a recent fabric analysis of roller-stamped *unguentaria* from London suggests that the roller stamps were used on pottery there possibly as early as the first century.[72]

The expansion of the use of the hollow voussoirs and the simplification of their manufacture during the second century are probably reflections of broader changes in terracotta production at this time. As P. Tyers points out, the visit of Hadrian to Britain and the subsequent construction of the Wall created a movement northward and general expansion of the pottery industry.[73] The distribution of the roller stamps on box-tiles and hollow voussoirs supports the picture of an expanding and more complex distribution mode than had been present at the end of the first century CE. Evidence suggests a combination of distribution modes: local production for a specific site, production at a single workshop that is distributed regionally to building sites, and itinerant tile makers who could have either set up shop at a site or hired out communal kilns near the building site.[74]

Used wisely, the hollow voussoirs could have both increased comfort and decreased fuel costs, so one must wonder why did they not catch on in the other northern provinces with similar climatic conditions, such as northern Gaul and Germany, where Caesar notes the cold climate was even more severe than in Britain.[75] The answer must lie in the nature of the development of the terracotta industry in Britain. It was a unique province in that it was largely an aceramic culture until the first century BCE when Julius Caesar's attempt at conquest strengthened the ties with Roman culture as it percolated up through Gaul, which had a long tradition of terracotta production. With the invasion of Claudius and even earlier,[76] new cultural habits were introduced, including different styles of eating that required different types of vessels, new modes of food preparation that required mortars and pestles, and new forms of leisure activities including bathing, which required new types of terracotta building elements. Northern Gallic potters had already migrated into southern Britain before the invasion, as demonstrated by a Gallic type kiln excavated at a workshop in Chichester,[77] but with the invasion came another wave of immigrant craftsmen from Gaul seeking new markets. There was no established industry to tap into so they developed networks from scratch to fulfill the needs as they arose.

The hollow voussoirs were developed in a corner of southern Britain, but as shown by the Westhampnett-type voussoirs found at Bath, the idea soon spread. Then during the second century the voussoirs were made by a variety of workshops, and itinerant tile makers plied their craft during a period of rapid expansion in both urban and villa contexts. The hollow voussoirs were a special-order item, but in a province that was undergoing rapid development in a brief period, there was sufficient demand to make their manufacture a worthwhile endeavor for a tile maker. One reason the hollow voussoirs were confined largely to Britain, in spite of its operational benefits for the baths, is probably that there were long established manufacturing and trading traditions elsewhere. In the cultures of Gaul and Germany, which were increasingly moving toward mass production of pottery, a production model that included handcrafted items for a particular building was perhaps not appealing or practical as a long-term investment. The sporadic occurrences at Xanten and Bliesbruck are most likely explained by tile makers from Britain who relocated and brought their technological skill and craftsmanship with them. The hollow voussoirs in Britain are unique in providing a rare glimpse into innovations in bath technology and terracotta production that are untainted by preexisting terracotta traditions.

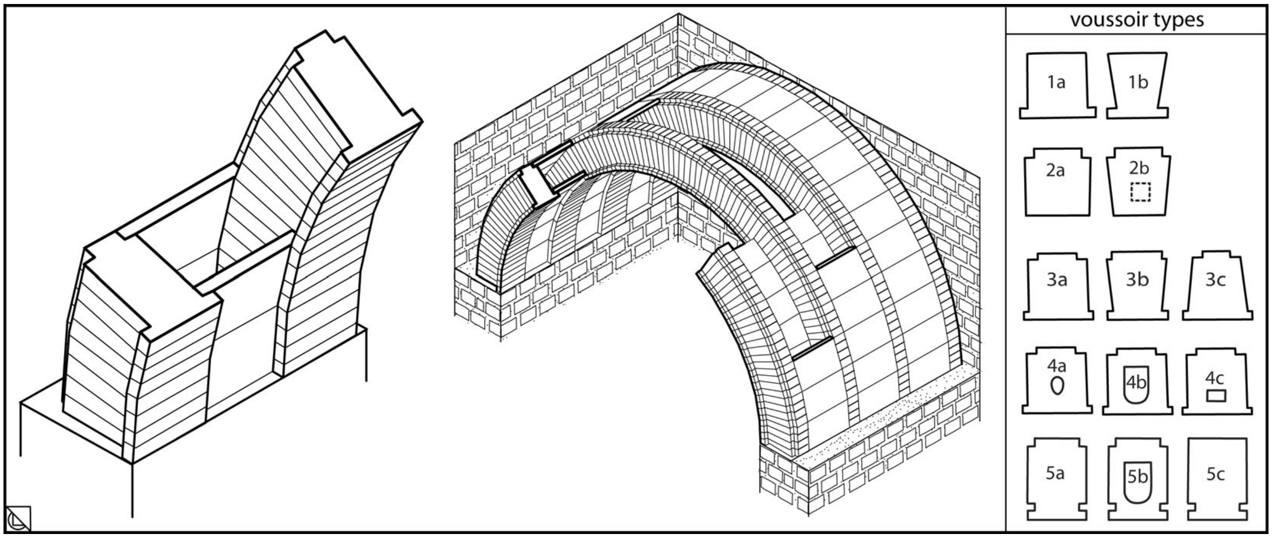
7

VAULTING RIBS OF ARMCHAIR VOUSSOIRS

The last of the techniques examined in this study is a vaulting system that, like the hollow voussoirs of Chapter 6, was used primarily in bath buildings. It is made up of a series of spaced ribs that supported flat tiles between them. The ribs were made of "armchair voussoirs," a type of voussoir made of terracotta or occasionally of stone that has flanges along the bottom (intrados) and/or rebates at the top (extrados) (Fig. 101). Because it was used to create arched ribs it is also known as a "rib voussoir."[1] In the past, the general assessment of this technique was that one of its primary purposes in its fully developed form (i.e., with two covering tiles as shown in Fig. 101) was to create heated vaults, but as we discover, this may not always be the case. The armchair voussoirs occur in the western empire, and a majority are found in small villa baths. They can be grouped into four geographic regions: France, Iberia, Morocco, and Britain (Fig. 102). The increased popularity of this technique during the early empire sheds light on the social and economic development of these western provinces and on how they changed during Late Antiquity. Questions asked include the following: Where and when did the invention first occur? Where and when was it most commonly used? What was the original purpose of the technique, and how did it change over time? What were the parameters that governed its diffusion? What can these patterns of diffusion reveal about the broader social and economic context in which it occurred?

The armchair voussoir system was relatively fragile, so finding examples in situ is rare. Consequently, much of the material now lies in storerooms. Thus my discussion of dating and use relies heavily on excavation reports and the observations of others, rather than on personal examination of the material, and it is intended as a starting point for future investigation rather than as a definitive assessment. The study of armchair voussoirs has been aided immensely by M. Fincker's article (1986) on them and A. Bouet's (1999) book on terracotta building elements in Gallia Narbonensis, which is the area of their greatest concentration. Bouet developed a typology for the Gallic examples, which I apply to the voussoirs found outside his area of study (Fig. 101). The primary publications of armchair voussoirs have tended to be regional studies, so one goal of this chapter is to provide a synthesis of the use of this technique across regions.[2] The examples shown on the distribution map (Fig. 102) and listed in the catalog (WebCat. 7-A) represent a compilation of these regional studies along with more recent finds, thereby enabling a more global assessment.

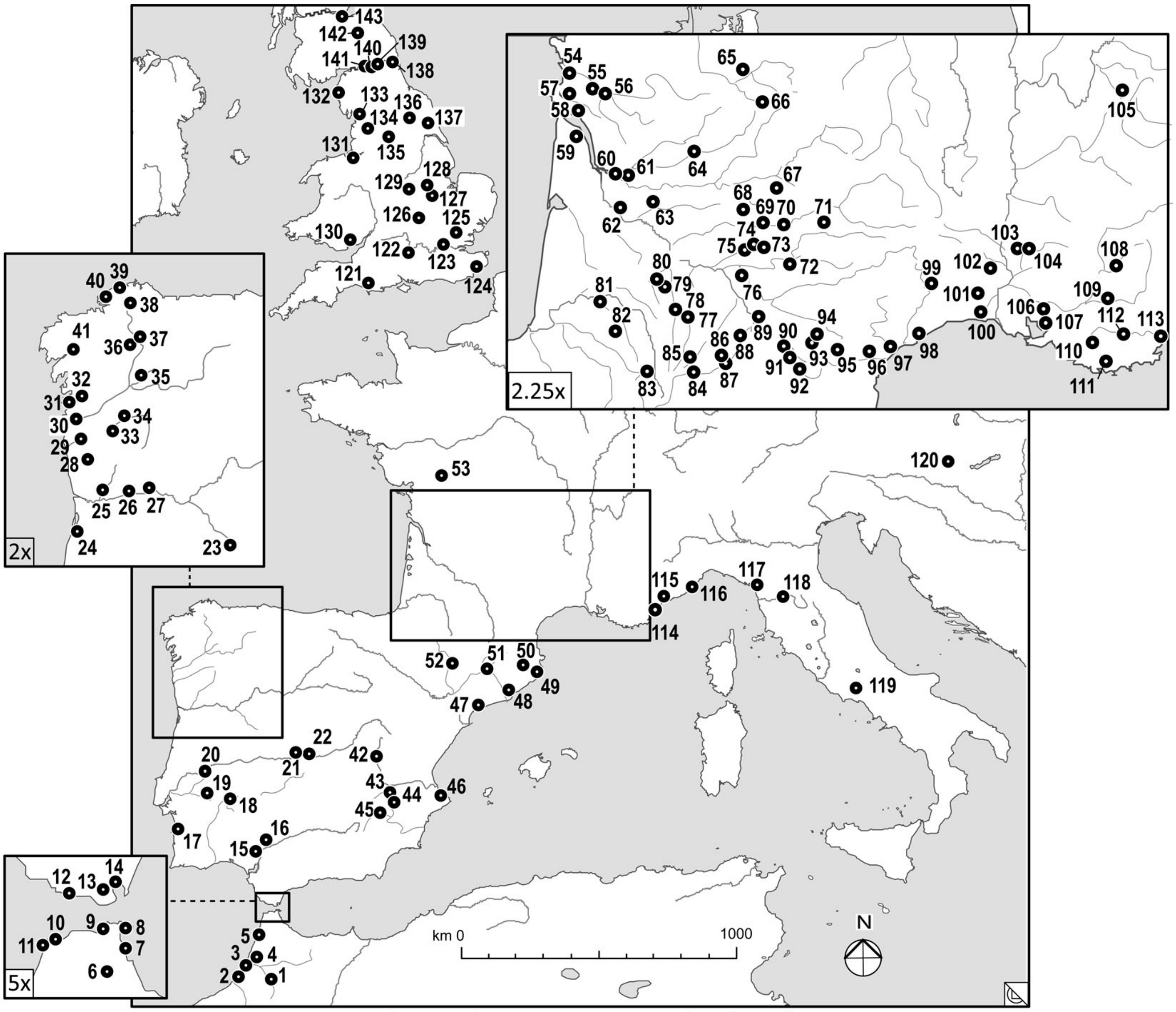
Catalogs (WebCat.) and color figures (WebFig.) can be downloaded at www.cambridge.org/vaulting



101. Drawing of armchair voussoir vault using double slabs. Right: chart of voussoir types based on those established in Bouet 1999.

PRECURSORS: FLANGED TERRACOTTA BARS

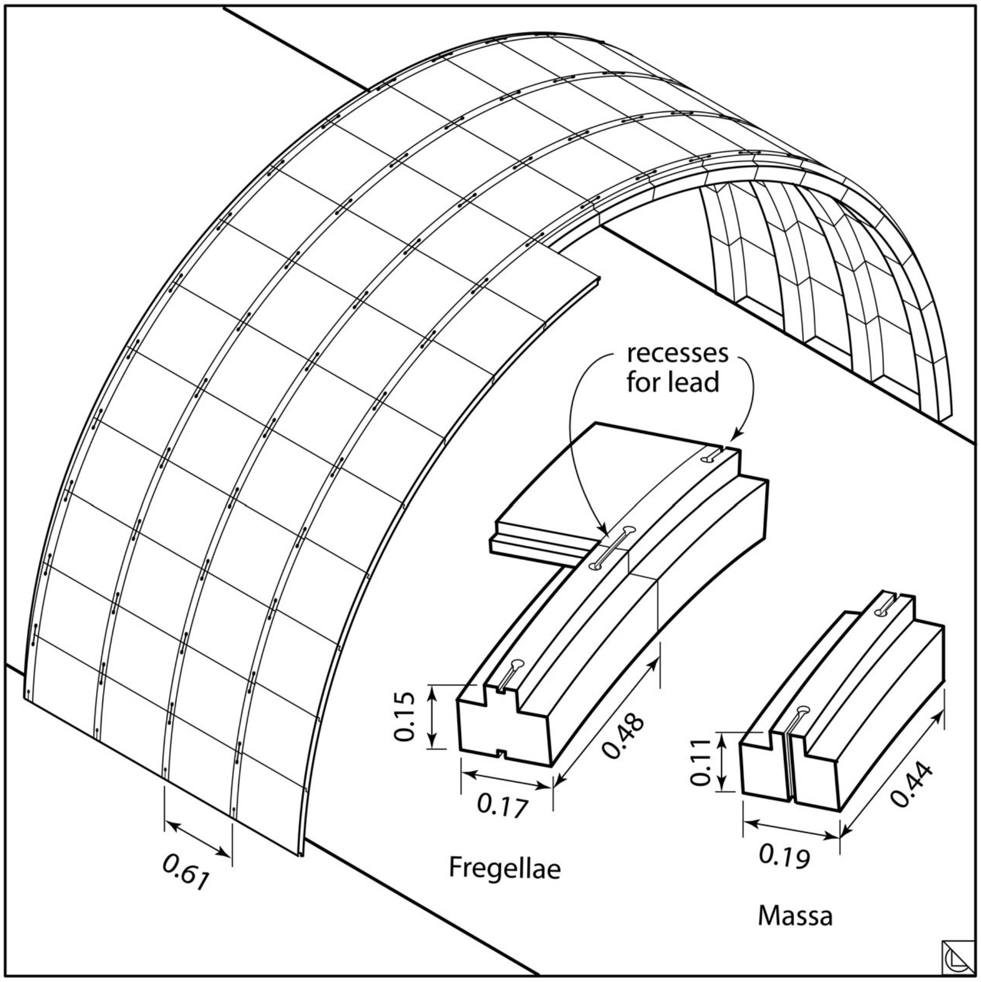
A precursor to the armchair voussoirs occurs in a Republican bath building at Fregellae in Latium. Pieces of terracotta bars with flanges were found built into the foundations and scattered throughout the bath. The material has not been published in detail, but four different modules have been reported. The two largest ones have vertical holes at either end; some of these holes have grooves along the extrados and the intrados into which (molten?) lead was added to connect adjacent bars (Fig. 103). The lead was found still attached to some of the bars, though most had been taken by scavengers, who often broke the bars to extract it.[3] V. Tsiolis reconstructs a semicircular vault with a span of about 6 m (based on the curvature of the bars), which he assigns to the room closest to that width, the likely *apodyterium/tepidarium* of the men's section of the bath. The 15 cm thick bars would have created a vault with a thickness to diameter ratio (t:D) greater than 1:36, which is much higher than the theoretically possible ratio of 1:17.6 (see Chapter 1). Therefore, some method of resisting the tension within the vault would have been necessary to stabilize it, and this may account for the presence of the lead connectors. Finally, among the bars were also found curved *sesquipedales* (44 cm square), which were specially formed to fit the larger modules and would have spanned between them. Remains of plaster were found along the intrados of the *sesquipedales*, but the extrados showed no sign of exterior treatment, so the system was likely used simply to construct the inner ceiling, which was then covered by a wooden roof structure. The bath had two phases. The first has been dated to the third century BCE and the second to the second quarter of the second century BCE. Some of the smaller bars were found packed into the foundations of the phase 2 bath, thus implying their use in phase 1, whereas the larger bars are attributed to phase 2.[4] The whole complex has a definite *terminus ante quem* of 125 BCE when the town rebelled against the Romans and was subsequently destroyed.[5] The phase 2 bath is the earliest known in Italy to have used *suspensurae* of *pilae* instead of canals for the hypocaust, to have used terracotta tubes for wall heating, and to have both male



Sites With Armchair Voussoirs and Related Forms

1 *Volubilis*, **2** *Sala*, **3** *Thamusida*, **4** *Banasa*, **5** *Lixus*, **6** *Tamuda*, **7** Sidi Bou Hayel, **8** Puertas del Campo a Ceuta, **9** Marsa, **10** Gandori, **11** *Cotta*, **12** *Baelo Claudia*, **13** Los Barrios, **14** *Carteia*, **15** Italica, **16** *Munigua*, **17** Mirobriga, **18** Badajoz, **19** Estremoz, **20** Comenda, **21** Tavalera de la Reina, **22** Toledo, **23** La Alberca, **24** Cacia, **25** *Tongobriga*, **26** Fonte do Milho, **27** Quinta da Ribeira, **28** Braga, **29** Ponte de Lima, **30** Currás, **31** Toralla, **32** Vigo, **33** Muradella, **34** Vilar de Santos, **35** Castillós, **36** Santa Eulalia de Bóveda, **37** Lugo, **38** Vilar da Graña, **39** Gandarela, **40** Noville, **41** Cirro, **42** Valeria, **43** La Igualada, **44** Chincilla, **45** Ontur, **46** L'Almadrava, **47** Tarragona, **48** *Baetulo*, **49** Llafranc, **50** Girona, **51** Solsona, **52** *Labitolosa*, **53** Sanxay, **54** Saint-Aignan, **55** Saintes, **56** Rouffiac, **57** Saint-Agnant, **58** Barzan, **59** Saint-Germain-d'Esteuil, **60** Lugon, **61** Barraud, **62** Loupiac, **63** Sainte-Colombe-de-Duras, **64** Périgueux, **65** Limoges, **66** La Croisille-sur-Briance, **67** Mayrinhac-Lentour, **68** Lavercantière, **69** Saint-Géry, **70** Cajarc, **71** Saint-Cyprien, **72** Saint-Martin-Laguépie, **73** Montdoumerc, **74** Saint-Paul-de-Loubressac, **75** Flaugnac, **76** Montauban, **77** Auch, **78** Ordan-Larroque, **79** Mouchan, **80** Montréal, **81** Saint-Sever, **82** Lalonquette, **83** Pouzac, **84** Valentine, **85** Montmaurin, **86** Cazéres, **87** Saint-Vincent-de-Couladère, **88** Muret, **89** Toulouse, **90** Mas-Saintes-Puelles, **91** Mireval-Lauragais, **92** Mazerolles-du-Razès, **93** Saint-Denis, **94** Les Martys, **95** Peyriac-Minervois, **96** Sallèles d'Aude, **97** Sauvian, **98** Lupian, **99** Montoulieu, **100** Saint-Gilles, **101** Nîmes, **102** Gaujac, **103** Roaix, **104** Vaison-la-Romaine, **105** Faverges, **106** Lambese, **107** Coudoux, **108** Digne-les-Bains, **109** Riez, **110** Tourves, **111** *Olbia*, **112** Taradeau, **113** Fréjus, **114** Anthéor, **115** Cimiez (Nice), **116** Albenga, **117** Massa, **118** Vingone, **119** *Fregellae*, **120** Zalalovo, **121** Dorchester, **122** Silchester, **123** London, **124** Dover, **125** Chagnall St. James, **126** Stanton Low, **127** *Durobrivae*, **128** Barnack, **129** Leicester, **130** Caerleon, **131** Chester/Holt, **132** Ravenglass, **133** Lancaster, **134** Ribchester, **135** Grimescar, **136** York, **137** Bainton, **138** Wallsend, **139** Chesters, **140** Chesterholm, **141** Great Chesters, **142** Newstead, **143** Bridgeness

102. Distribution map of armchair voussoirs (WebCat. 7-A).



103. Author's drawing of vault made of terracotta bars with details of bars found at the Republican baths at Fregellae, Italy (third–second century BCE) (based on Tsiolis 2001; Tsiolis 2006). Similar type bar found at a workshop in Massa (late second to mid-first century BCE) shown at lower right (details provided by E. J. Shepherd).

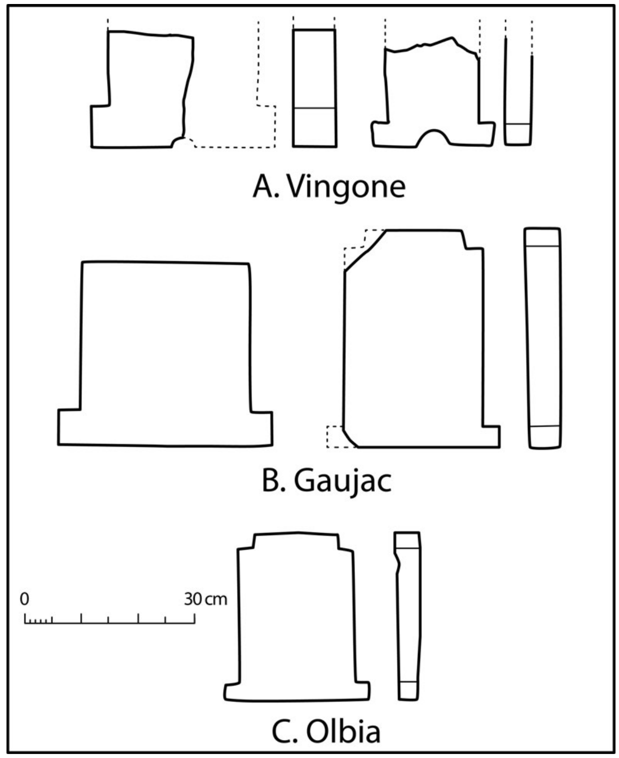
and female bathing sections;[6] therefore, the vaulting is only one of the many advanced features in this building.

The examples at Fregellae are the best known ones, but other finds suggest that the terracotta bars were not unique in Italy. A kiln site recently excavated in Piazza Mazzini in the heart of Massa near Carrara revealed fragments of terracotta bars very similar in size to the ones found at Fregellae.[7] They too have recesses modeled into either end for housing connectors of some sort, but the configuration is slightly different, as shown in Figure 103. The bars were found in the workshop and therefore were never used, so there is no evidence for the type of connector that filled the grooves. The site is dated by pottery finds from the late second century to the mid-first century BCE. Elsewhere, tantalizing hints of unusual vaulting also appear in a preliminary report of a Greek-type public bath at Caulonia (third century BCE) in southern Italy; the photographs show what appear to be bars of some sort from the fallen vault of one of the rooms (c. 8 m span), but definitive evidence awaits further publication.[8] In any case, the examples from Fregellae and Massa indicate that this was a technique in use in Italy from the third to the first century BCE, and future excavations may well reveal more examples.

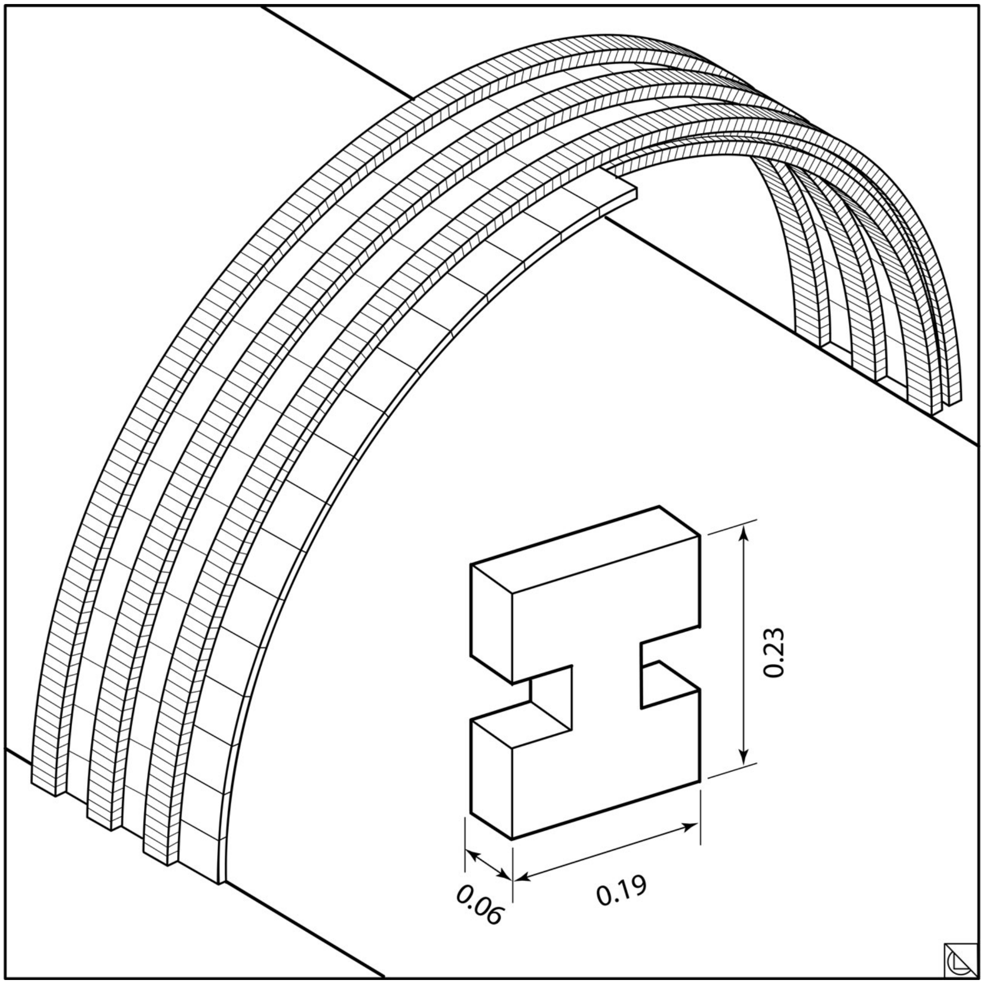
EARLY TERRACOTTA ARMCHAIR VOUSSOIRS

Vaulting ribs made of armchair voussoirs replaced the terracotta bars by the early first century CE, but where and when this first occurred is unclear. The earliest examples of the armchair voussoirs come from a workshop site at Vingone outside of Florence. The tiles have flanges projecting at the bottom (intrados) (Types 1a–b) (Fig. 104A). The thickest one (7.0 cm) is rectangular in form, whereas the thinner ones (4.0 cm thick) are trapezoidal; both are rectangular in section as opposed to wedge shaped, and neither type preserved its full height. As with the terracotta bars, the tiles would have created ribs, with the flanges supporting terracotta slabs in between. The examples from Vingone are unique in having a roughly semicircular cutout along the bottom edge such that a continuous groove would have been formed along the intrados of each rib. Also found in the workshop were roof tiles, amphoras, tableware, and cookware. Its most intense period of activity was 20 BCE–20 CE. The structure for which these armchair voussoirs were manufactured is not known, but unpublished armchair voussoirs have also been reported from Florence itself, thus suggesting that the products from the workshop may have been destined for the colony (ancient Florentia).[9]

Another early example of vaults made of ribs to support tiles (Fig. 105) occurs outside of Italy at a bath at ancient Baetulo in southern Spain. Instead of forming ribs in a T-shape, the Baetulo tiles are in the form of an H, with notches on either side (23 × 19 × 6 cm) that created a groove to support rectangular tiles (38 × 30 × 6 cm). This method was used to create the ceilings over both the *caldarium* (5.9 m span) and the *tepidarium* (5.2 m span), which formed the core of the bath. Unfortunately the dating of this building is somewhat uncertain, so placing it within a developmental chronology is difficult. J. Guitart Durán, in his original excavation report in 1976, dated it provisionally to the mid-first century CE. After finding no diagnostic material for the date in a test trench, he turned to stylistic analogies of the *caldarium* mosaics, the row-type plan of the bath, and fragments of pilaster capitals, admitting that none provided very precise criteria. However, in 1990 he was prompted to revise his assessment of the date to the mid-first century BCE after the publication of more



104. Early examples of armchair voussoirs. A: Terracotta workshop at Vingone, Italy (after Shepherd 2008: fig. 182). B: Bath B at Gaujac, France (after Bouet 1999: fig. 50d). C: North Baths at Olbia (after Bouet 1999: fig. 54c).



105. Bath at Baetulo, Spain (first century BCE to first century CE). Reconstruction of vault (c. 6 m) made with H-shaped voussoirs supporting tile slabs (based on Guitart Durán 1976: fig. 9).

information on the development of Republican era baths.[10] A bath with a similar plan was excavated at Valencia (ancient Valentia) and dated to the second century, just after the foundation of the city in 138 BCE. The Baetulo bath has a fairly primitive heating system in which only the hot pool was heated using two vaulted canals, rather than the more sophisticated hypocaust floor supported by *pilae*. On this basis, he has suggested the earlier date, which would put construction of the bath soon after the foundation of the city during the second quarter of the first century BCE; however, he indicates that there are still no stratigraphical data to confirm either of the proposed dates.[11] This H-type voussoir, which is unusually thick (6 cm as compared to 2–4 cm of later armchair voussoirs), could indicate an early stage in the development of what would become the standard armchair voussoirs (Types 1–3). Smaller H-type bricks have been found in northern Gaul and Germany, but whether they were used as voussoirs is unclear.[12]

Baetulo is only 20 km south of Cabrera de Mar where the unusual early vaulting tubes (Chapter 5) were used in a bath from the mid-second century

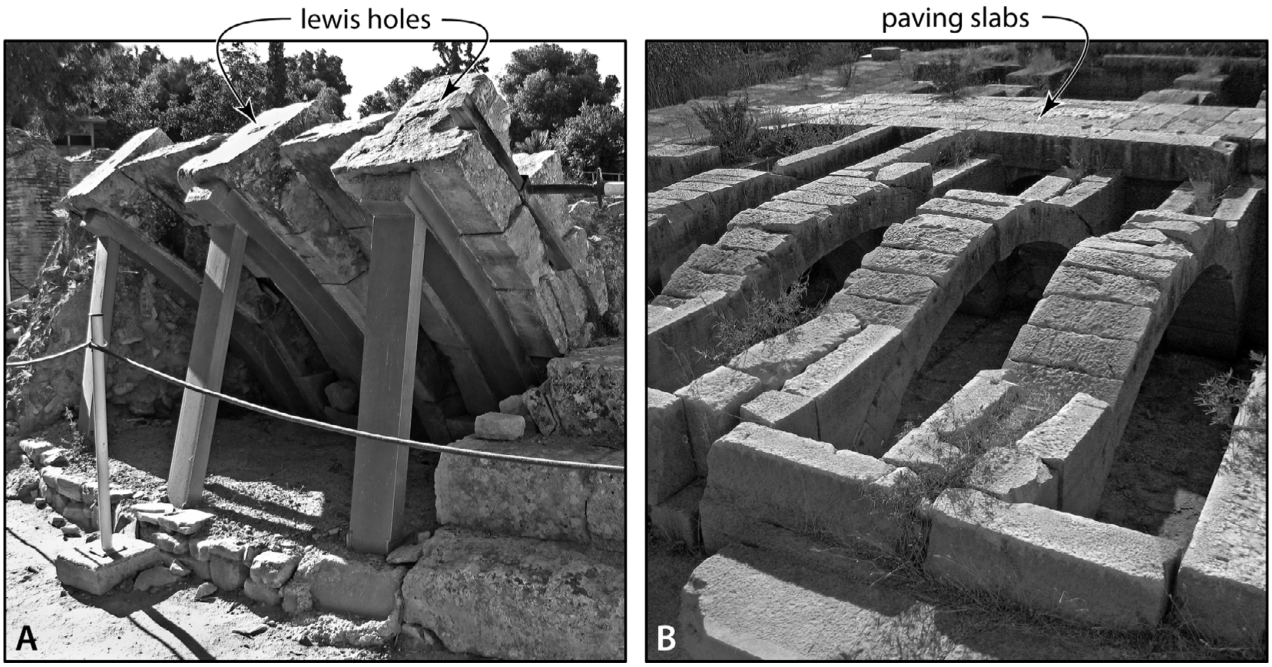
BCE. If the Baetulo vault dates from as early as the mid-first century BCE, these two baths buildings in Catalonia point to this region as a particularly rich area of terracotta ingenuity during the late Republic. The first century BCE was a period of intense interaction between Italy and the southern coasts of Spain and Gaul through war, trade, and colonization. Precisely when and where the shift from using terracotta bars to terracotta tiles took place is difficult to say, but it was clearly part of the fertile development of the spread of public bathing during the late Republic.

Ultimately, the armchair voussoirs took root in southern France where the densest distribution is found (Fig. 102). Early armchair voussoirs occur in Bath B at the Gallic *oppidum* of Gaujac and in the North Bath at the Greek colony of Olbia (modern Hyères-les-Palmiers). Bouet, who excavated at Bath B in Gaujac in the 1990s, shows two types: Type 1a (flanges only = single slab) and 3a (rebates and flanges = double slab; Fig. 104B).[13] J. Charmasson, who published the bath in 2003, illustrates only Type 1a and notes that they were found in rooms 1 (unheated) and 9 (heated). He restores them as forming the arch over a doorway, but as Bouet points out this is highly unlikely given their typical purpose as vaulting ribs.[14] Charmasson dates the bath to around 20–30 CE based on excavated finds, whereas Bouet takes this evidence as a *terminus post quem* and opts for a more general mid-first-century date.[15] At Olbia, a Type 3a (double-slab) voussoir was found at the North Bath dating to the Tiberian period (14–37 CE; Fig. 104C). The bath functioned only until the late first century CE, as shown by lamps found deposited in its hypocaust. The location and context of the voussoir(s) are not noted in the publications.[16] Both heated rooms vented the hypocaust gas via vertical chimney flues built into their walls, so in spite of the accommodation for a double-slab vaulting system, any connection of the vault spaces to the heating system is unlikely.[17] The fact that the bath has such a circumscribed period of activity in the first century CE makes this one of the more securely dated early examples.

Pinpointing the precise date and location of the transition from the type of flanged bars used in Italy to the typical Type 1–3 armchair voussoirs is difficult based on present evidence, but there seems to have been strong cross-cultural exchanges between the Tyrrhenian coast of Italy and the southern coast of Spain and France. However, if we go back to the distinction between an "invention" (the eureka moment) and an "innovation" (the implementation of the invention), the latter is more important because it provides insight into the culture that adopts the technique, a topic discussed further at the end of this chapter. In this sense, the *innovation* of the armchair voussoirs seems to have occurred in southern Gaul and Spain where the technique achieved its greatest popularity, although clearly the initial idea for the concept of the ribbed terracotta ceilings had occurred earlier in the incipient phases of Roman bath development in Italy.

STONE ARMCHAIR VOUSSOIRS

At about the same time that the terracotta armchair voussoirs appeared, the same concept occurred in stone at the Augustan odeum at Gortyn on Crete. It is a unique use of the armchair voussoirs – they appear to have formed the annular vault supporting the cavea of the odeum (Fig. 106A). The system allowed for the ribs to remain the same width while the slabs were trapezoidal to fit the gap between the radiating ribs. The remaining ribs visible today belong to the Augustan phase of the building and were later incorporated into a late second-century CE reconstruction, perhaps as a type of ready-made formwork.[18] The blocks making up the ribs were of two types: an inverted T-type with flanges to support stone slabs and an H-type with a notch forming the groove

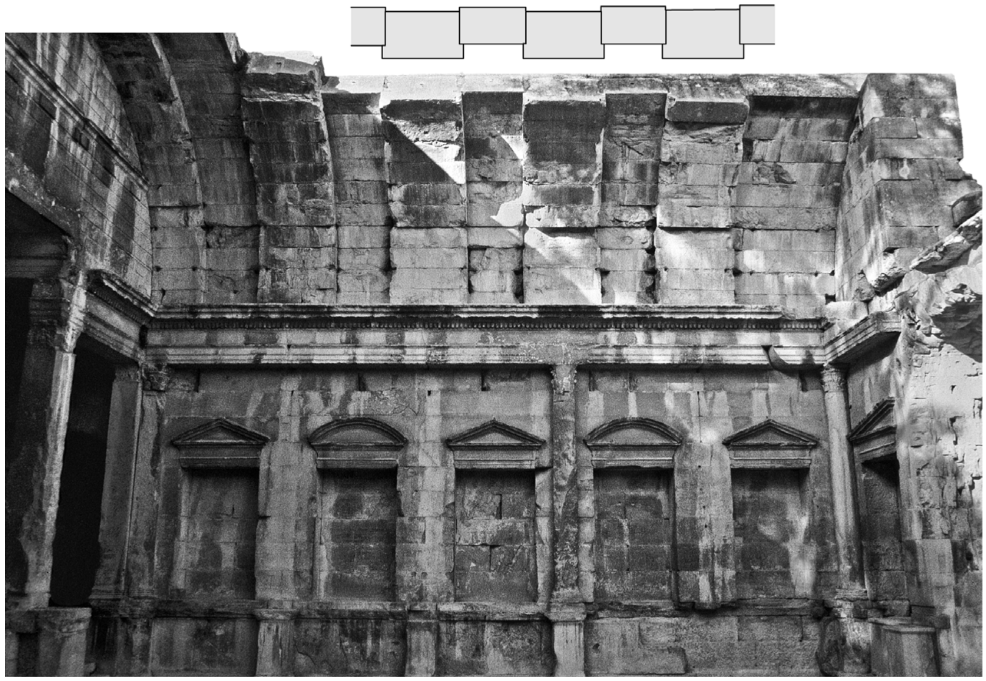


106. A: Odeum at Gortyn, Crete (Augustan) with stone armchair voussoirs supporting cavea. B: Crypt of the Temple of Apollo at Claros, Turkey (second century BCE) with arched ribs supporting floor slabs (photo: William Aylward).

into which the slabs were inserted. The blocks and slabs both retain the lewis holes used to lift and set them in place. This system uses the same principle as the terracotta examples in Italy and in southern Gaul, but at present any direct link between the two developments seems unlikely.

One factor influencing the use of the stone armchair voussoirs on Crete could be its central location at an important crossroads between mainland Greece and Egypt where there was a strong tradition both of stone carving and of Hellenistic bath building. An example of the types of experimentation that occurred can be seen in a mid-second-century BCE bath building at Taposiris Magna, 45 km west of Alexandria, where one of the vaults employed joggle joints in its voussoirs (for a similar configuration, see the example from Giza in Fig. 25), providing the earliest known example in stone.[19] Although not exactly the same as the armchair voussoirs, the two techniques share the concept of resting one stone on the projecting ledge of the one below. Another similar use of stone construction can be seen in the second-century BCE crypt of the Temple of Apollo at Claros (Fig. 106B) where a series of arches support the roofing slabs forming the paving of the sanctuary above.[20] The odeum at Gortyn is unusual in having one of the rare examples of armchair voussoirs that is not in a bath building, but its central location would have exposed it to the fertile tradition of stone carving in the Hellenistic world. Nevertheless, the armchair voussoir technique was not adopted in the Roman vaulting of the Greek East in either stone or terracotta, and the odeum at Gortyn remains anomalous.

One structure that could shed light on the development of the armchair voussoirs in Gaul is the "Temple of Diana" at Nîmes, which employed stone examples in its barrel-vaulted roof; however, its date is disputed, with some arguing for the Augustan period and others for the second century CE. The barrel vault (c. 9 m span) is built of a series of stone ribs



107. "Temple of Diana" at Nîmes, France. Barrel-vaulted roof built of stone armchair voussoirs supporting stone slabs in between. Above: diagram of block configuration in vault.

with narrow flanges carved along the intrados to support thick stone slabs (Fig. 107). The central vault is cleverly buttressed by smaller barrel-vaulted passages on each side. The main publication of the complex is that of R. Naumann (1937), who dated the vaulted structure ("Saalbau") to the first half of the second century CE.[21] Subsequently, several scholars (P. Gros, H. von Hesberg, and U. Gans) reevaluated Naumann's dating and proposed an Augustan date based mainly on stylistic aspects of the decorative motifs on the architectural elements (capitals, friezes).[22] Naumann admitted in his stylistic analysis that some elements displayed the simplicity that one expects of the Augustan period, but he saw other stylistic elements relating to the composition as a whole as more significant factors indicating a later date.[23] Most recently E. Thomas and J. Anderson have supported Naumann's original second-century dating of the monument.[24] From a structural and constructional standpoint, the large scale of such a freestanding vaulted structure seems more congruent with the later date.[25] As with the date, the function of the "Temple of Diana" is also unclear, though it appears to be part of a sanctuary; proposals include a temple of the imperial cult and/or a library.[26] Thus, it is a fascinating structure but not one that clarifies our understanding of the development of the armchair voussoirs.

A few other examples of stone armchair voussoirs are also known. Lightweight calcarenite armchair voussoirs were used together with terracotta ones at Bath 2 (4.5 m span) at Labitolosa in eastern Spain,[27] to be discussed later. In Britain, both stone and terracotta examples were found in a villa bath at Stanton Low (3.6 m span), where the excavator believed they belonged to different phases,[28] as was likely the case at Labitolosa. A few examples employing exclusively stone armchair voussoirs occur in military baths in Britain: calcareous tufa ones at Chesters (ancient Cilurnium; 4.0 m span) and Great Chesters (ancient Aesica; 5.2 m span) and sandstone ones at

Chesterholm (ancient Vindolana).[29] They appear to have been used in the same manner as the terracotta ones, but evidently were employed where terracotta production was less common. Given the small span of these baths, lightweight stones may have been chosen as much for their insulating properties as for weight reduction (on the effects of weight reduction, see Chapter 8).

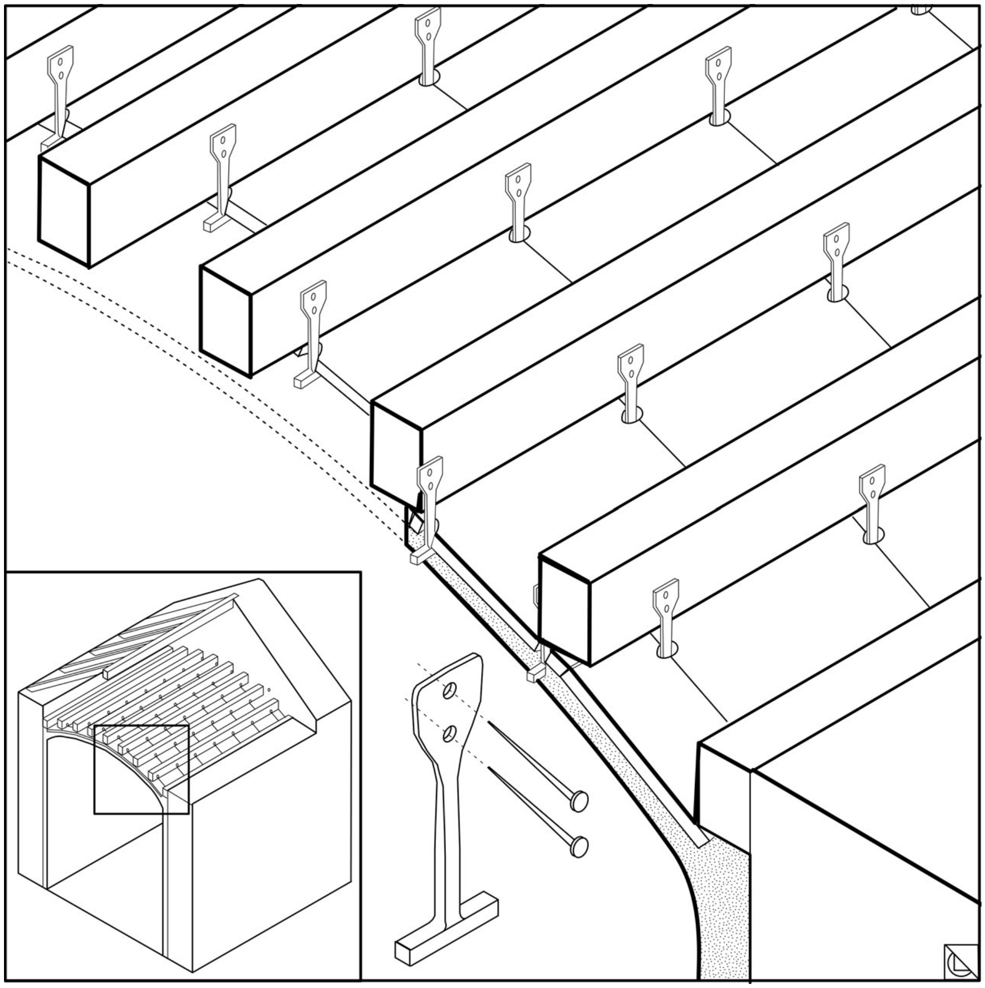
PURPOSE OF ARMCHAIR VOUSSOIR RIBBING

A number of purposes have been attributed to the armchair voussoir ribbing: to protect a wooden roof structure from the moisture generated in a bath, to aid in reducing centering and facilitating construction, to create a lightweight vault that minimized lateral thrusts, to create a permanent centering for concrete, and to provide heating. The stone examples at the Gortyn odeum and the "Temple of Diana" (regardless of its date) suggest that a primary motive was to facilitate construction. Likewise, most early terracotta examples in bath buildings had supports for only one layer of bricks – Fregellae (6 m span), Baetulo (5.9 m span), Vingone, and Gaujac (4–5 m span) – implying that the original intention was related to the construction process, rather than to any attempt to provide heated vaults. An advantage of the armchair voussoir system is that it could reduce the amount of wood and labor needed for centering. For small vaults (under c. 5 m span), each rib could be built individually and the centering frames reused for the next rib. For the stone examples where a crane had to be used (as demonstrated by the lewis holes at the odeum at Gortyn),[30] the ribs would have been built one by one, with the slabs positioned between each pair before the next rib was added in order to allow room for the lifting machinery.

The earliest vaulting system employing flanged ribs, at Fregellae, brings to mind Vitruvius's description of suspended vaults made of tiles hung from iron bars attached to wooden beams, a system that he recommended as a means of protecting the timbers from moisture:[31]

> The vaulted ceilings (*concamerationes*) will be more convenient if they are made of concrete [masonry] (*ex structura*).[32] But if they are of timber, they should be tiled underneath in the following fashion. Iron bars or arches are to be made and hung on the timber close together with iron hooks. And these rods or arches are to be placed so far apart that the tiles without raised edges may rest upon and be carried by them; thus the whole vaulting is finished resting upon iron. Of these vaulted ceilings the upper joints are to be stopped with clay and hair kneaded together. The underside, which looks to the pavement below, is to be first plastered with potsherds and lime pounded together and then finished with stucco or fine plaster. Such vaulting over hot baths will be more convenient if it is made double. For the moisture from the heat cannot attack the wood of the timbering but will be dispersed through the two vaults.

An example of Vitruvius's system, which employed iron hooks hanging from wooden beams, has been excavated at a second-century CE bath in the Piazza della Signoria in Florence, where it covered a room 11.5 m wide.[33] A more common system employed T-shaped hooks nailed to the beams (Fig. 108).[34] Both systems had the advantage of producing no outward thrust on the walls, especially when used for a large span like the one at Florence. The disadvantages included potential moisture (condensation) damage to the wood and iron, which is why Vitruvius also recommends using a double shell, although he never explains how it should be made. The development of concrete vaulting by the second half of the second century BCE in Italy provided a solution to the problem of moisture damage, although the hanging system clearly continued to be used in Italy, as demonstrated by the Florence example. The flanged terracotta ribs



108. Séviac villa baths at Montréal, France. Reconstruction of the hanging tile ceiling (based on Monturet and Rivière 1986: pl. 25).

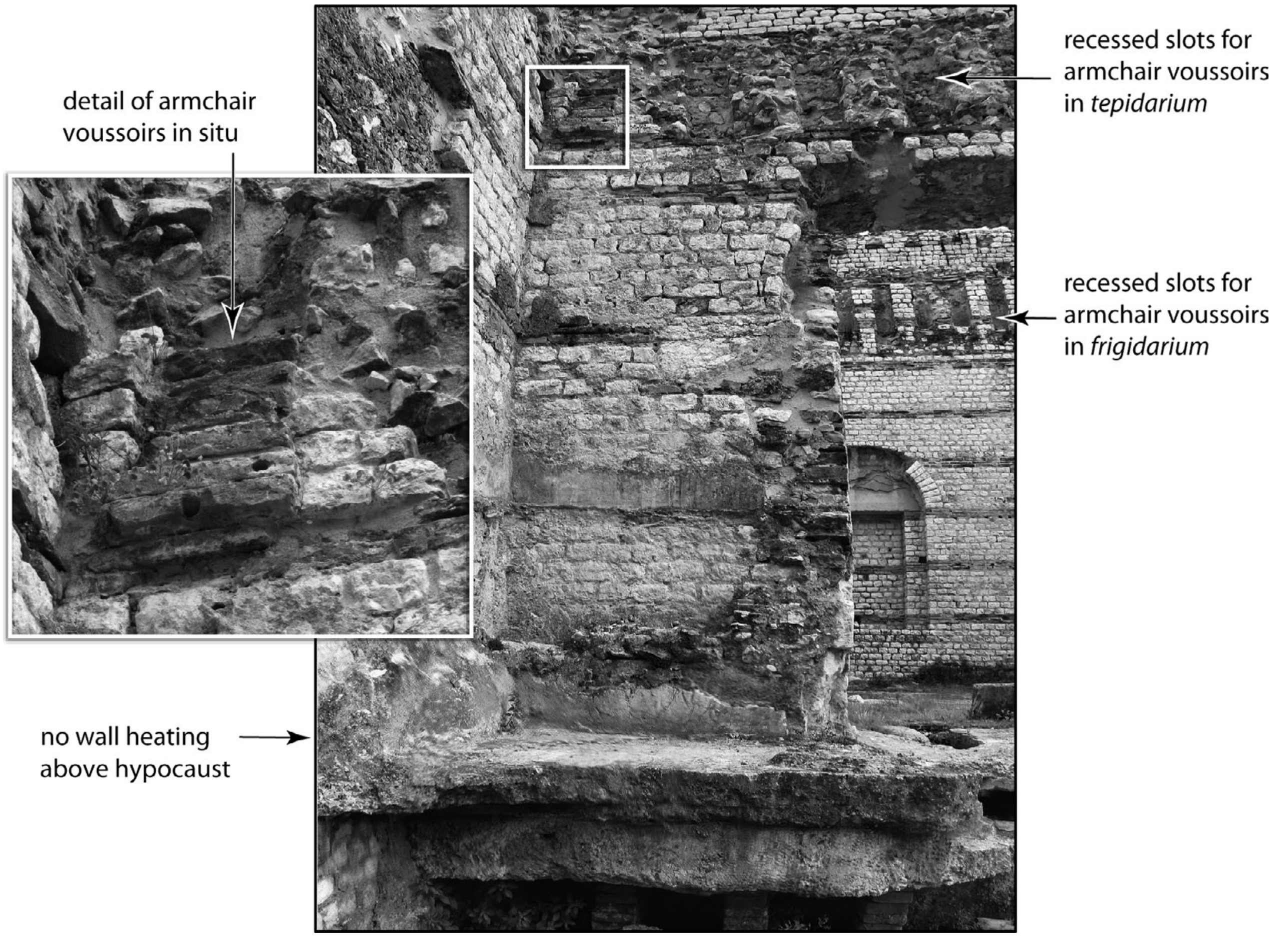
at Fregellae occurred before the adoption of *opus caementicium* vaulting in Italy and apparently represent an attempt to develop a moisture-proof roofing solution, much like the hanging vaults described by Vitruvius and the vaulting tubes at Morgantina and Cabrera de Mar (Chapter 5).

Another potential purpose suggested for the armchair system was to form a permanent centering for concrete. However, an examination of the available evidence suggests that armchair vaults were typically covered by wooden roof structures. Excavations at the ZAC des Halles site at Nîmes revealed armchair voussoirs in a public bath, parts of which clearly had a wooden roof, given that charred remains of beams destroyed in a fire were found over the *frigidarium* pool.[35] At the East Baths at Mirobriga, the excavators found roof tiles above the layer of fallen armchair vaulting from the *frigidarium* pool and concluded that the vault was likely covered by a wooden roof supporting the tiles.[36] At Labitolosa in southeastern Spain, both stone voussoir vaults over the heated rooms of Bath 1 (mid-first century CE) lacked any mortar sealant and must have been covered by a tiled wooden roof, as was the unvaulted *frigidarium* where terracotta antefixes were recovered. Likewise, the roof tiles covering the *frigidarium* of Bath 2 at Labitolosa (third quarter of first century CE) were found on the floor, and the excavators assume that the wooden structure extended to cover the armchair vaults of the heated rooms.[37] In the Séviac villa at Montréal (Fig. 108), the ceiling over the pool of the *frigidarium* was found to have been of flat tiles supported by the T-shape hooks nailed to wooden beams, whereas the hot rooms of the early phases apparently employed armchair voussoirs.[38] Similar iron hooks were found at the Moulin du Fâ baths at Barzan, where armchair voussoirs (Type 4c, double slab) that probably once covered its *caldarium* (7.2 m span) were found reused as *pilae*.[39] The roof structure over the armchair vaults at Séviac and Barzan is not known, but given the hanging vaults with the iron hooks a tiled wooden roof is likely.

The only example ever cited for armchair voussoirs supporting a concrete roof is the North Baths at Cimiez (ancient Cemenelum) in a suburb of Nice,[40] but a close examination reveals that the situation is not so clear-cut. The roofing has sometimes been reconstructed with the armchair ribs supporting two slabs and a concrete fill above,[41] but the reconstruction drawing in the original report by F. Benoit only shows the bottom slab and no concrete – although it does show the voussoirs with both flanges and rebates to support two slabs.[42] He notes, "Large segments of these arches comprising the armchair voussoirs with the covering slabs in place, the intrados of which still had lime plaster preserved, were found with their concrete bedding (*lit de béton*) in the position where they fell."[43] In the published photos, the plaster along the intrados is clearly visible, but the meaning of "*lit de béton*" is less clear because there is no concrete visible in the photographs.[44] However, the voussoirs are apparently held together with mortar, so he was probably referring to the bedding of mortar *between* the voussoirs (i.e., the mortar joints), but his use of the word *béton* instead of *mortier* led to the interpretation that there was actually concrete above the vault. In fact, the structural analysis presented in Chapter 8 shows that the outer wall of the *frigidarium* was not thick enough to counter the additional lateral thrust that would have been imposed by a concrete roof over this nine-meter wide vault. The same would be true for the *frigidarium* of the nearby Porte d'Orée Baths at Fréjus (ancient Forum Julii), which is the only other armchair vault of this scale and the only other one with the housing for the voussoirs remaining in situ.[45] Benoit dated the North Baths to the third century, but an earlier date in the late first or second century CE has recently been proposed.[46] Likewise, the excavated material from the Porte d'Orée Baths points to a second-century date.[47] From a structural standpoint, both of these vaults should have been covered by a wooden tiled roof. If so, there is no evidence to suggest that the armchair vaults were ever used as a permanent centering for concrete.

HEATED VAULTS?

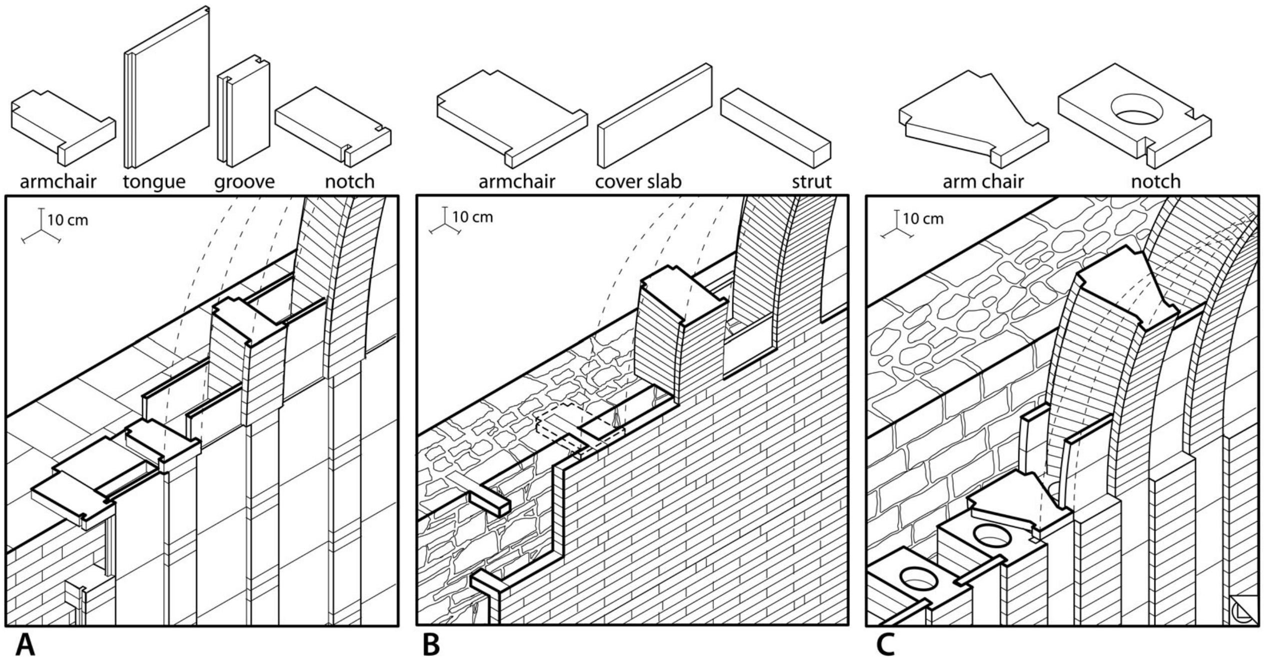
The armchair voussoir ribbing is used almost exclusively for the vaults of baths, so the type with double slabs (most common) has often been said to form a type of heated vault (like the hollow voussoirs in Chapter 6). However, as we have seen, the single-slab type appeared in the earliest baths (Fregellae, Baetulo, Gaujac); only after the second slab was used to form an enclosed channel could the system have been used for heating purposes. Bouet suggests that heated vaulting began toward the end of the first century CE in Gaul when the Type 3 voussoirs with both flanges and rebates became more common.[48] However, the armchair voussoir from Olbia from the first half of the first century CE had both flanges and rebates for two slabs (Fig. 104C), but as discussed previously, there was no wall heating to supply hot air. The North Baths at Cimiez are also instructive. The large pieces of fallen vault mentioned earlier were found



109. North Baths at Cimiez (Nice), France (ancient Cemenelum). View of *tepidarium* looking into *frigidarium* in background. Inset shows detail of armchair voussoirs remaining in situ. Slots for similar armchair voussoirs visible in vertical slots in *frigidarium* wall. Note that there was no wall heating in the *tepidarium*, so the vaults could not have been heated. (Color image: WebFig. 31).

in the *frigidarium*, yet they employed Type 3 (double-slab) armchair voussoirs. The adjacent room, the *tepidarium*, also employed armchair voussoirs, some of which still remain in the vertical slots from which the ribs sprang. This room had a hypocaust floor, but no wall heating system (Fig. 109, WebFig. 31). The *caldaria* did have walls heated with box-tiles, but no evidence remains for the vaulting of these rooms.[49] All of these examples demonstrate that the use of the double-slab system does not necessarily indicate that the vaults were heated. This raises the question as to whether the armchair system was ever used in conjunction with the heating system. Unfortunately, heated walls are nowhere preserved high enough to show a connection to the vault channels, so any evidence must be indirect.

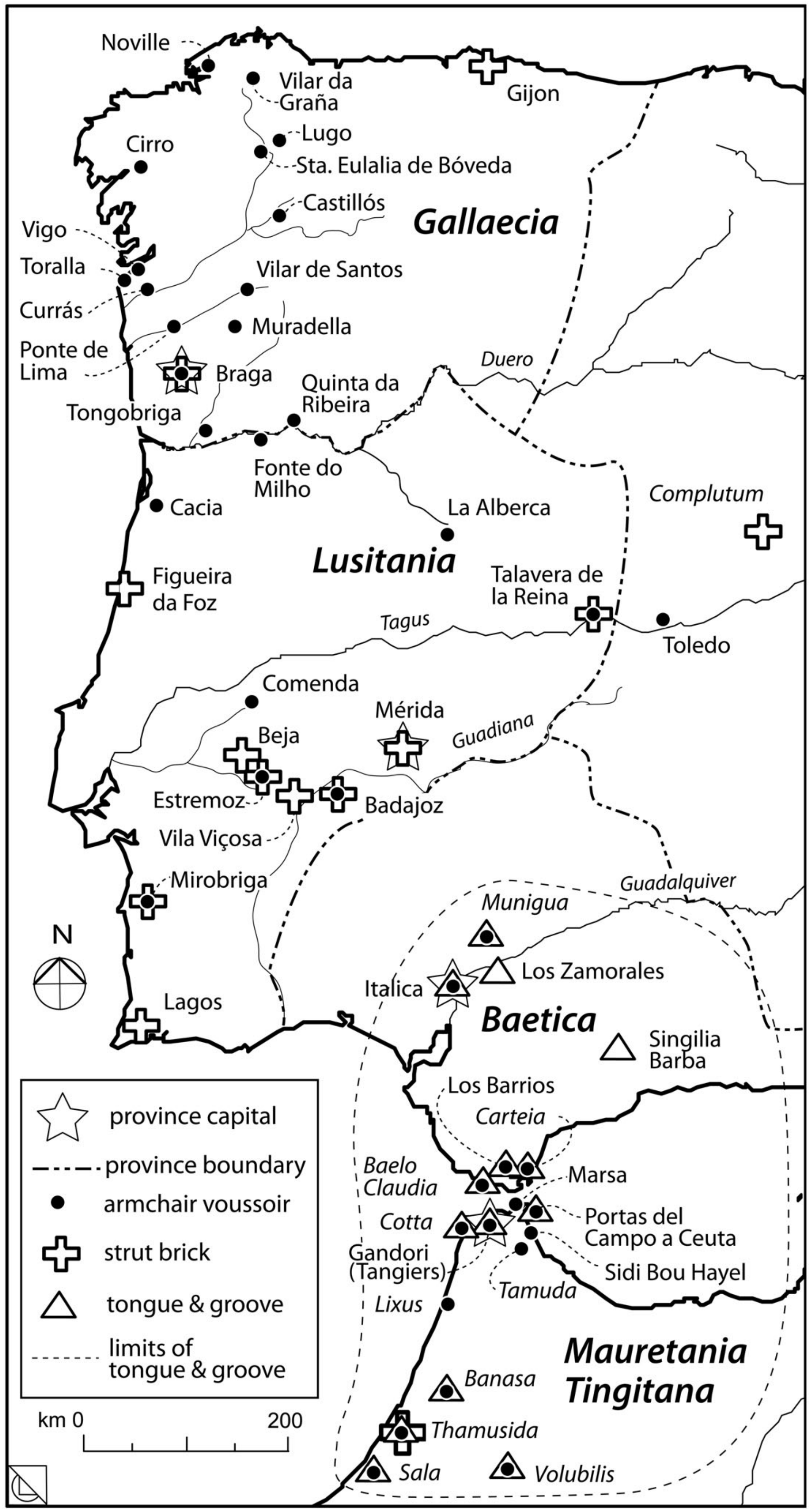
Some suggestive evidence for heated vaults comes from new types of wall heating systems that were created in Iberia and often used together with the double-slab armchair voussoirs. The first is what I call the "tongue and groove" system. It consists of three modules: a tile with projecting "tongues" on the two long sides, a corresponding tile with "grooves" on the long side, and a tile with notches on both sides,



110. Reconstruction of different types of wall heating systems used with armchair voussoirs in Iberia and Morocco. A: Tongue and groove system at the baths at Thamusida, Morocco (based on Camporeale 2008b). B: Strut system at the baths at Mirobriga, Portugal. C: Unique system at baths at Tongobriga, Portugal (based on Tavares Dias 1997). Brick types at top are those found in excavations.

which was built into the wall so that it projected and formed the spacer that held the other bricks in place (Fig. 110A). The best documented example of the tongue and groove system combined with armchair vaulting comes from the late second-century Thermes de Fleuves at Thamusida in Morocco where parts of the wall system remain in situ.[50] The system worked similarly to the *tegula mammata* and spacer peg/tube systems in that it did not channel the hot air into vertical wall flues, but rather allowed the air to flow freely within the airspace. The distribution map in Figure 111 shows where one or more of the elements making up the tongue and groove wall heating system have been found (WebCat. 7-B,C). As demonstrated, they often occur together with armchair voussoirs. If the vaults were connected to the heating system, one advantage is that the ribs could be positioned over the notched bricks so that the airspaces between them would be aligned over the airspaces of the wall and the hot air could enter directly into the vault channels (Fig. 110A).

The earliest evidence for the terracotta elements making up the tongue and groove wall heating system comes from the region around the Bay of Gibraltar. In the baths at ancient Carteia, the grooved-type bricks were found reused in a wall dating to the early second century CE; therefore, the bricks themselves must have been produced during the first century and used previously in a different context. The bath may have also employed armchair voussoirs, because examples have been found in the local museum of the Casa de la Cultura de San Roque, where the excavated Carteia material is stored, but the precise provenance of these is not documented.[51] A. Torrecilla Aznar also cites examples of tongue bricks from the workshop of La Venta del Carmen just outside Carteia, which was active during the first century.[52] Other evidence was found in the first-century parts of

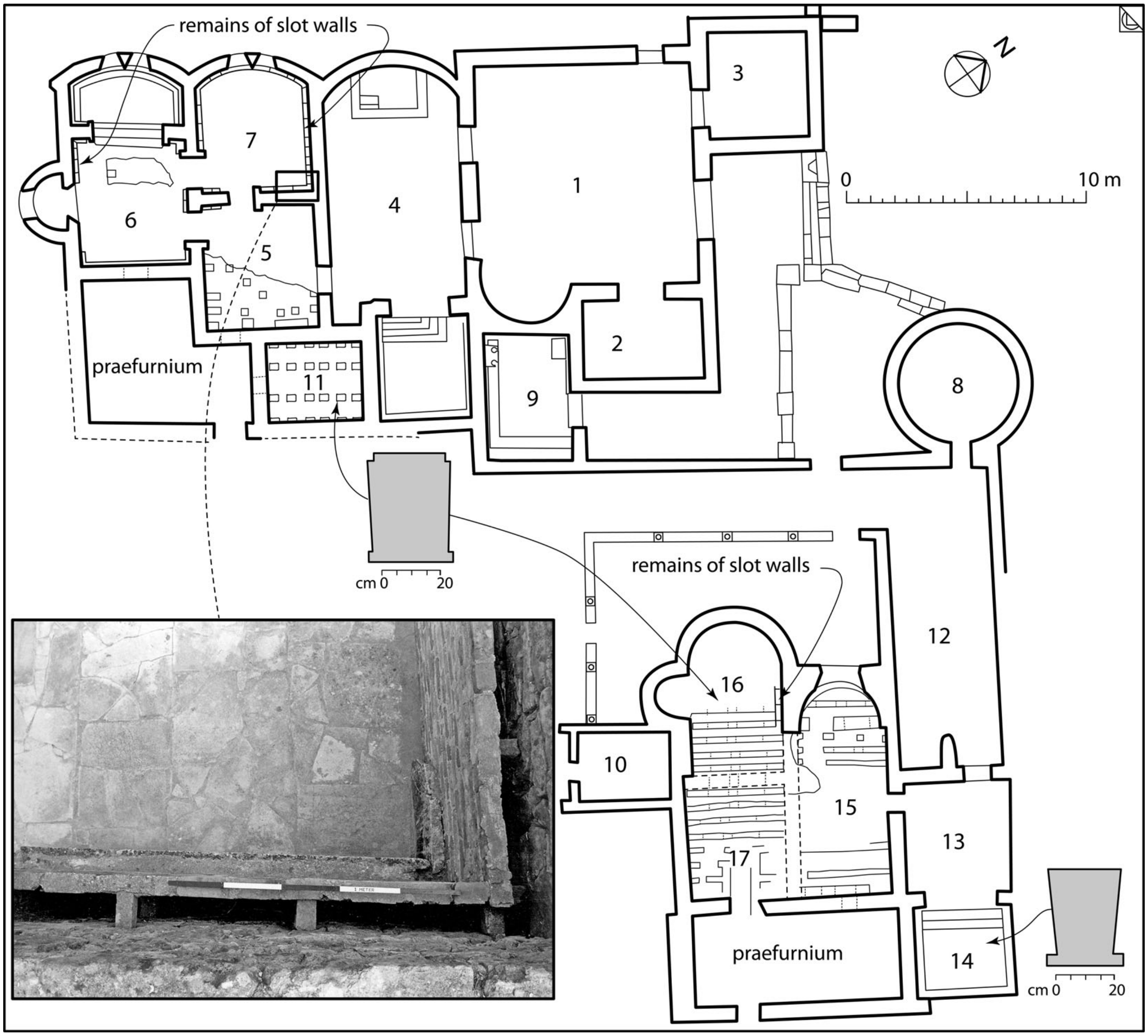


111. Distribution map showing findspots of armchair voussoirs in relation to those of tiles from the tongue and groove wall heating system and the strut wall heating system (WebCat. 7-B,C).

the nearby Puente Grande villa at Los Barrios, where fragments of all three types of tongue and groove tiles were found along with an end fragment of an armchair voussoir with its rebates.[53] These fragmentary finds around Carteia suggest that the new wall heating system was created alongside the armchair voussoir system, which may well have been introduced via trade contacts with southern Gaul. Some experimentation with the tongue and groove system, however, had already occurred in Bath 1 at Labitolosa (mid-first century CE), where the sandstone blocks of the walls of the *tepidarium* and *caldarium* have vertical channels, which are each supplied with vertical grooves carved along the two sides into which thin terracotta slabs were inserted to form flues.[54] The bath did not employ armchair voussoirs, but Bath 2, built a generation later, did use them, albeit without the tongue and groove wall heating system.[55] In Spain, the distribution of the tongue and groove wall heating system is limited to Baetica, but it also spread across the Strait to Morocco, usually together with armchair voussoirs (WebCat. 5-B).

A second type of wall heating system, which is often found used with armchair voussoirs, is best documented in the baths at Mirobriga (Figs. 110B, 112). The wall cavity (c. 14 cm) was formed by building up the inner wall of thin bricks, usually 5 cm square in section and 30–35 cm long, which was then connected to the main structural wall with the same type of bricks laid perpendicular to form the "struts" between the two. This strut heating system at Mirobriga belongs to construction phases dated to the second half of the second century CE[56] but the system seems to have been developed much earlier. Some walls in the Flavian phase of the Thermes de Flueves at Thamusida have the remains of similar struts that were cut off when the bath was renovated in the late second century.[57] All the other examples of the long thin bricks used for the strut system have been found thus far in Portugal and northern Spain at various sites and in museum collections (WebCat. 7-C). They are found together with armchair voussoirs at baths in villas of El Saucedo (Talavera de la Reina, Spain), La Cocosa (Badajoz, Portugal), and Santa Vitoria do Ameixal (Estremoz, Portugal) (Fig. 111).[58] Unfortunately most of these are not datable. As with the notched bricks of the tongue and groove system, the use of the strut system would have provided a more stable inner wall to support the armchair voussoirs if the vault was meant to be heated, but alas no evidence from the upper parts of any of the walls remains to confirm how the armchair ribs were set onto the impost.

A singular combination of tile types was found in the excavation of the baths at Tongobriga in northern Portugal, which may also provide evidence for a heated vault (Fig. 110C). A number of different shapes of tiles were excavated, including three types of armchair voussoirs, which relate to at least two different phases of the vaults. Also found were notched tiles with large holes in the center. The walls of the bath (c. 90 cm thick) were built of *opus vittatum* using the local granite as facing. The *tepidarium* (4.9 m wide) and *caldarium* (4.5 m wide) walls show no signs of holes for attaching heating elements, so the excavator has reconstructed the notched bricks as forming inner walls (c. 42 cm thick) built up against the *opus vittatum* walls such that they created a series of rectangular vertical flues between them, as well as round vertical flues within. The armchair voussoir ribs would have rested on these inner walls while the *opus vittatum* walls extended up to support a wooden truss above.[59] The reconstruction is not entirely without problems;[60] nevertheless, the existence of both notched bricks and armchair voussoirs suggests that the builders were experimenting with the heating system using elements similar to those at Labitolosa and Carteia, possibly as a means of developing a system by



112. Plan of East and West Baths at Mirobriga, Portugal (after Biers and Biers 1988: fig. 79), showing where armchair voussoirs were found. Inset photograph of the remains of the strut wall heating system (photo: Jane Biers).

which the heating in the walls could be transferred to the vaults.

The invention of two new types of wall heating systems in Iberia, the tongue and groove system and the strut system, that were both used in conjunction with the armchair voussoirs may imply that the wall heating systems were connected to the vaults. In heated rooms that employed more traditional wall heating systems of box-tiles, *tegulae mammatae*, or spacer tubes/pegs attached to the wall surface, the heat could have been directed into the vault by means of vents built into the top of the wall. However, none of the walls has survived to a sufficient height to provide evidence for vents, although such vents are known at the base of hypocaust walls and for chimneys.[61] Nevertheless, we do know that double-slab armchair voussoirs were used in unheated rooms at Cimiez and Olbia, so the use of two slabs does not always indicate that a vault was heated. The system also could have offered sufficient structural, constructional, and thermal insulation benefits to justify its use without being directly connected to a wall heating system. Finally, should the distinction between single-slab and double-slab armchair voussoir systems be considered as a chronological indicator (i.e., is the double-slab system a more developed and later version of the original single-slab system)? The double-slab system is certainly more common; 79 percent of the voussoirs that can be assigned an identifiable type (85/107) belong to it. The single-slab system was developed first, as seen at Fregellae, Baetulo, and Gaujac, but in some cases the two systems were used together. For example, the East Baths at Mirobriga (second half of second century CE) employed the single-slab system over the pool in the *frigidarium* (rm 14, 4.2 m span), and remains of the double-slab system were found in the debris in the *caldarium* (rm 16, 3.5 m span).[62] So, the distinction is not necessarily one of chronology – room function can also be a factor.

PRODUCTION MODES AND DIFFUSION

The terracotta armchair voussoirs are limited to baths in the western Mediterranean (n = 144). The greatest concentration is in France (44%) followed by the Iberian peninsula (29%), Britain (16%), and Morocco (14%). An examination of the known brick stamps on armchair voussoirs along with the types of contexts in which the baths occur provides a better understanding of the factors governing the decision to use the technique and, with it, a more holistic view of social and economic trends over time.

Early examples in both France and Iberia appear in small public baths (Gaujac, Olbia, Labitolosa, Tongobriga) during the first century CE, whereas later they are concentrated mainly in private villa baths. In Gaul, they were used for public baths at only ten of sixty-four sites for which the armchair voussoirs are documented, and most of these can be dated to the first or early second century. In Gaul, the transition from public to private seems to have begun by the early second century CE. Indeed, this was a boom time for villa construction in Aquitania and Narbonensis.[63] The proliferation of the armchair voussoirs from the second century is strongly linked with the growth of villa culture. The vaults are usually quite small (3–5 m span), and the technique provided a way to build them quickly and economically. A question that arises is why the technique did not spread into other parts of Gaul, and there are no doubt numerous factors at work. One could be geographical connectivity. The armchair voussoirs occur along trade routes: the Garonne river valley, the southern coast of France and Spain, and the Atlantic coast of Portugal and Morocco. A more likely factor, at least at the regional scale, was the interactions between the people, particularly the villa owners themselves. The bath houses added to the villas were not simply for use by the residents. Like dining rooms, they provided the setting for social interactions with guests. So the proliferation of the armchair vaults in villa baths probably reflects a type of social network that created a market among the aspiring elites, who used their villas as places for competitive display and entertainment.

Armchair voussoirs do not usually bear stamps, but those that do provide some insight into the supply system. The only producer thus far known to have stamped the armchair voussoirs from Gaul is the well-documented Clarianus, whose material has a wide distribution along the southern part of the Rhone and its tributaries.[64] The stamped voussoirs occur at Vaison-la-Romaine in the bath of the Maison du Buste en Argent and at nearby Roaix in an unidentified context. Unstamped armchair voussoirs have also been found along with box-tiles stamped by Clarianus at the *mansio* baths at Faverges, suggesting that he may have supplied those as well.[65] His workshop, the largest one known in Gaul, made a variety of terracotta building elements, including standard bricks for walls and also bath tiles such as *pilae* tiles, box-tiles, and *tegulae mammatae*. It was active from at least the time of Hadrian with its peak activity in the mid-second century. Its location is not known, but Bouet speculates that it was likely near Vienne, where there is a concentration of Clarianus stamps.[66] Worth noting, however, is that with the exception of Faverges, there is little correlation between the distribution of Clarianus's other products and the sites employing armchair voussoirs. Bouet notes that there are regional distribution patterns of some types of armchair voussoirs within the larger distribution in southern Gaul,[67] but associating them with particular workshops is difficult given the lack of both stamps and reliable dating evidence.

In the region of modern Catalonia in Spain, another example of a stamped armchair voussoir bore the name of Quietus, who was one of six known producers in a workshop at Llafranc. His stamp is also found on bricks, *tegulae*, and *imbrices*.[68] The Llafranc workshop produced a variety of terracotta products, including flat bricks, box-tiles, circular bricks for *suspensurae*, and amphoras. Of the six producers known at Llafranc, only Quietus's stamp (QVIETI retro) is found on armchair voussoirs. One of the other Llafranc stamps (P VSVL VEIENT), which occurs on *tegulae*, can probably be reconstructed with the *tria nomina* of P. Usulenus Veiento, who also stamped Pascual 1 amphoras.[69] Beyond the environs of Llafranc, Quietus's products were found 25 km up the coast at Ampurias (ancient Emporiae), which seems to have been the main recipient of the Llafranc tiles; however, his products have been documented also at the villa of Tolegassos outside of Ampurias.[70] Because both Llafranc and Ampurias are located on the coast, transport was likely by ship, which is also suggested by the production of amphoras in the same workshop. The only other workshop producing armchair voussoirs in this area was at Ermedàs, farther inland between Girona and Banyoles. It had a mixed production including roof tiles, various types of bath tiles, and common ware.[71] Precise dating for the armchair voussoirs at both workshops is not possible, but they appear to belong to the second century CE.

J. Tremoleda has related the production of bath tiles at the workshops of Llafranc and Ermedàs to the trend of adding small baths to the local villas. He notes that the villas themselves usually had wattle and daub or mud brick walls, so the real necessity for architectural tiles (other than column bricks and roof tiles) only came with the popularity of adding bath buildings to the *pars urbana* of the villas in the surrounding region, which began in the second century.[72] This pattern corresponds to that noted in Narbonensis and Aquitania, where the armchair voussoirs appeared first in public baths during the first century and then became part of the villa architectural vocabulary during the second century.

In Britain, the stamps tell a different story, because at least some of the production was clearly the work of the military. Of the twenty-four sites with armchair voussoirs, thirteen can be associated with the military, two are villa sites, and the remaining nine are uncategorized. Three of the sites (Bainton, Durobrivae, and York) have armchair voussoirs stamped by the Legio IX Hispania (LEG IX HISP), based at York from approximately 71 to 120 CE.[73] Unstamped armchair voussoirs have also been found at the military workshop at Holt,[74] which from the latter part of the first century supplied the legionary fort at Chester where the Legio XX Valeria Victrix was stationed. Other armchair voussoirs were found near York at a workshop at Grimescar that produced tiles and pottery for the fort at Slack during the first quarter of the second century. They were unstamped, but roof tiles at the workshop bore the stamp COH.IIII.BRE of the Cohors IV Breucorum from Pannonia.[75] Also found there was a diploma of 103 CE for the centurion, Reburrus, a Spanish name,[76] which raises the possibility that military recruitment from areas employing the armchairs voussoirs was one means of technology transfer into Britain. However, some evidence may suggest that civilian workshops produced armchair voussoirs even earlier. At the site of the supposed "Governor's Palace" in London, armchair voussoirs were found made in a distinctive fabric (Museum of London fabric 2454), which links them to the Eccles villa in north Kent, which produced great supplies of tiles for London during the period 50–70/80 CE. The use of the same fabric for the voussoirs therefore may indicate their occurrence during that time.[77] Thus the military was producing the armchair voussoirs in Britain by the early second century, but whether they introduced the idea is less clear. Nevertheless it seems to have been a major agent of diffusion within Britain. Likewise, the one anomalous example from the auxiliary fort at Zalalovo (ancient Sala) in Hungary (first century CE) may be explained in the same way.[78]

Stamped armchair voussoirs from Mauretania Tingitana also provide some evidence for production. Examples bearing the imperial seals ANTO AVG, EX FIGVL CAESA, and IMP AVG have been found in northern Morocco at Tamuda, the site of a Roman military camp. Preliminary microscopic analysis of the fabric suggests that they were produced nearby.[79] A workshop producing materials with similar stamps was identified by wasters at Gandori outside of Tangiers; these materials included IMP AVG stamps on armchair voussoirs and the tongue-type bricks of the tongue and groove wall heating system. Other types of tiles in the same workshop were found bearing imperial stamps: HADRI AVG, ANTO AVG, and EX FIGVL CAES. The use of imperial stamps at both military sites suggests that the camps may have been established on imperial property. No military stamps have been found at Tamuda, but at Gandori tiles were found bearing the stamp C∞ (*C*(*ohors*) (*milliaria*)), which should refer to the auxiliary unit, Cohors II Syrorum milliaria equitata sagittaria civium Romanorum.[80]

This evidence implies that both military and imperial stamps were being used in the same workshop, though not necessarily in the same period. The use of military and imperial stamps in the same workshop is also attested in Britain at Carlisle where tiles bearing military stamps of Legio II and Legio XX have been found with others bearing IMP stamps (in contexts dated to 170–183 CE).[81] Indeed, archaeometric studies of stamped bricks and tiles from Thamusida show that military and imperial production supplemented private production in Tingitana until the mid-second century after which the number of private producers increased.[82] The finding of both military and imperial stamps at the same workshop at Gandori suggests a role for the military in the urbanization of Mauretania Tingitana.[83] But even so, the use of the armchair voussoirs along with the tongue and groove wall heating system, which we saw appeared already during the first century around Carteia, is a distinctly regional phenomenon that was not created or imposed by the military or any other external agent.

The IMP AVG stamps also appear on armchair voussoirs and tongue-type bricks at a bath at Baelo Claudia on the opposite side of the Strait of Gibraltar.[84] No evidence for the production of such tiles has been found in the area around Baelo, thus leading to the belief that they were shipped across the strait. The evidence is intriguing both for the stamps' appearance on both sides of the strait and for the type of bricks on which they occur. The form of the IMP AVG stamps appears in a number of variations, and Ponsich proposed that one of the types was earlier (perhaps mid-third century) than the others, with the remaining ones, including those from Baelo, dating to the end of the third century CE. He based his dating on coin finds and on the appearance of the IMP AVG stamps in other contexts – Tangiers, Cotta, Lixus, and Tamuda – that he considered to be from the third century or later. He reasoned that the stamps that do not mention a particular emperor (i.e., EX FIGVL CAES and IMP AVG) should date to a late period when the *res privata* (personal property) of the emperor had become part of the imperial *fiscus* and therefore had passed to the holder of the throne rather than through family lines.[85] However, the baths at Baelo, in which the IMP AVG stamps were found, have recently been redated to an earlier period, which is relevant to our understanding of when and how the armchair voussoirs were introduced into Tingitana.

The excavators at Baelo Claudia have reexamined the materials from the bath excavation and proposed an earlier date for the bath, possibly as early as the first half of the second century.[86] They note that the finds from a sealed context under the floors of the bath do not extend beyond the first century CE and that the construction technique used is similar to other second-century buildings at Baelo, such as the macellum. The earlier dating should not be problematic from either an epigraphical or juridical standpoint. As E. M. Steinby has shown with regard to brick stamps in Rome, the emperor could own lands as part of his private family wealth (*res privata*) alongside property that belonged to the imperial *patrimonium* or *fiscus*, so the existence of both specific and generic imperial stamps need not imply a chronological distinction and could simply refer to the two types of imperial properties.[87] If the IMP AVG stamps are much earlier than proposed by Ponsich, then the imperial production of the tongue and groove wall heating system could have begun in Tingitana by the first half of the second century.

CONCLUSIONS

The development of the idea of using flanged ribs to create terracotta vaults dates back to the third century BCE, but the precise dating for the move to ribs made of armchair voussoirs is more difficult to determine; nevertheless, the outlines of a pattern of development can be sketched. So far the earliest published example of the concept of using flanged ribs as vaulting elements is at Fregellae in central Italy where flanged terracotta bars were employed in both the original third-century BCE phase of the bath building and in the second-phase remodeling (second quarter of the second century BCE), yet the recently discovered examples at Massa indicate that the technique was known elsewhere. The H-type voussoirs at the Baetulo bath may represent a second stage of development, but the earliest true armchair voussoirs (Bouet Types 1–3) that can be reasonably well dated occur at the Vingone workshop in Italy (active 20 BCE–20 CE) and in southern France during the first half of the first century CE in the North Bath at Olbia and at Bath B at Gaujac. By the Flavian period, the armchair voussoirs also appear in Iberia (Carteia, Labitolosa, Tongobriga). The area of greatest concentration, however, was in Narbonensis and Aquitania where their use spanned from the first through the fourth centuries. The first-century examples were mainly in small public baths, and the technique seems to have become popular as part of the urbanization process.

The original function of the armchair ribs was clearly to aid in the construction process by offering an easy to build moisture-proof vault that required a minimum of centering. For vaults that spanned more than about five meters, the armchair ribs could have also provided some structural advantage by lightening their load. There is little evidence that the armchair voussoir vaults ever formed a permanent centering for a concrete roof, and in fact, they were likely used to avoid having to build a costly and heavy roof structure. Most, if not all, would have been covered with timber structures. If the vaults were ever heated, this development was secondary. The most suggestive evidence for heated vaults comes from around the Bay of Gibraltar during the second half of the first century with the development of the tongue and groove wall heating system, which was often used together with the armchair voussoir vaults. Another wall heating system, using terracotta struts, found mainly in Lusitania and Gallaecia, was sometimes employed together with the armchair voussoir vaults. It too may have been used in conjunction with heated armchair vaults, but there is no definitive evidence. Regardless of whether the vaults were heated or not, the armchair technique clearly provided an easy way to build economical vaulted ceilings. For developing provinces it was an ideal method, and it ultimately became particularly common for small privately owned villa baths in Gaul and Iberia.

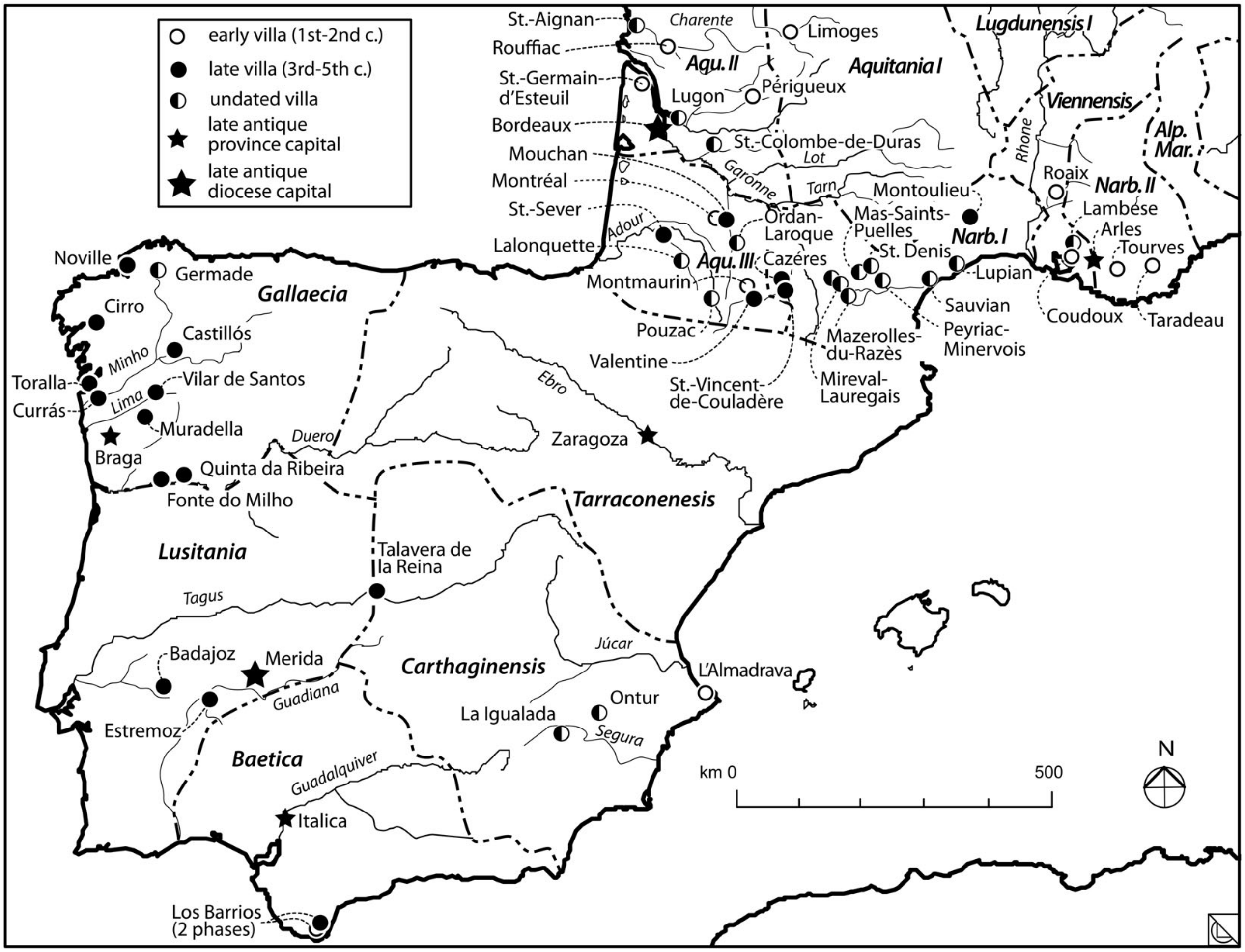
One of the questions posed in the beginning of the chapter was: What can patterns of diffusion reveal about the broader social and economic context in which they occurred? The early examples of armchair voussoirs in Gaul appeared at a time when the production of amphoras for transporting local wine was also increasing, as demonstrated by the fact that the local Gallic amphoras began to replace the Italian Dressel 1.[88] Viticulture in Gaul expanded greatly after the spate of colonization under Caesar and Augustus at the end of the first century BCE. Early use of armchair voussoirs then appeared during the first half of the first century CE in Narbonensis (Olbia, Gaujac), in the region where many of the amphora workshops were located. The use of the armchair voussoirs increased dramatically in the late first and early second century CE as the rural villas that were once focused mainly on production began to receive upgrades with the building of more luxurious living accommodations that often included private baths. In general, the production facilities of villas have been less well excavated than the grand residences (though this situation is changing[89]), so associating the products of villa workshops with the terracotta elements of baths in the same villa is rarely possible. However, on the south coast of Narbonensis the workshop of Le Bourbou supplied both wine amphoras and terracotta tiles for the nearby villa of Prés-Bas near Loupian, and armchair voussoirs have been found at both sites.[90] Though the workshop at Llafranc in Spain was in an urban context, the fact that it was producing amphoras alongside building tiles demonstrates that the two endeavors were connected, at least at coastal sites. Thus one of the catalysts for the adoption of the armchair voussoirs was no doubt the synergy between urbanization and agricultural production, mainly of wine and oil, that provided the wealth that fueled the architectural upgrades in the cities and the villas surrounding them.

In Iberia the period of greatest change leading to the construction of bath buildings began during the Flavian period. Indeed, the last quarter of the first century is when we see the earliest examples in Iberia of Type 3 armchair voussoirs (double slab) in public baths at Carteia, Labitolosa (Bath 2), and farther north at Tongobriga. This was also a period of experimentation with wall heating systems, such as the unusual example in Bath 1 at Labitolosa. The increased trade of wine, oil, and metals along the southern coast of Spain and France no doubt aided the flow of ideas and technological exchange during the first century. The area around the Bay of Gibraltar seems to have been important in the initial use and dissemination of the tongue and groove wall heating system, along with the armchair vaults that often accompanied it. Moreover, the exchange of technology between Baetica and Mauretania Tingitana is demonstrated by the appearance of the IMP AVG stamps on both the armchair voussoirs and on the elements of the tongue and groove wall heating system in northern Morocco and across the Strait of Gibraltar at Baelo Claudia, which according to Strabo was the main receiving point for goods shipped to and from Tingis (modern Tangiers).[91] The interdependence between the two areas is embodied in the term *Circulo de Estrecho* (Circle of the Strait), which originally referred to an economic region defined by the common exploitation of coastal marine resources, largely fish products such as garum.[92] The IMP AVG stamps and the use of tongue and groove wall heating are a testament to the longstanding and continued relationship between southern Spain and Morocco. That the connection continued into Late Antiquity is illustrated by the fact that Mauretania Tingitana was included in the diocese of Hispania rather than that of Africa, which included its neighbor Mauretania Caesariensis.

Three different patterns can be detected in the adoption of the armchair voussoirs. The first is in small public baths in Gaul and Iberia and later in Tingitana. They seem to be part of the developing phase of urbanization in each of these places. The second, mainly in Britain, relates to military expansion, again during a period of conquest and urbanization. Potential agents in this case could have been soldiers recruited from areas where the armchair voussoirs were used. The third pattern, and by far the most common one, is in small baths that were added to villas that clustered around the cities and towns that had developed during the phase of urbanization, a phenomenon particularly noticeable in Gaul and Iberia. A vast majority of all the baths using the armchair voussoirs have small vaults in the range of three to five meters. The two examples where they were used in large vaults are the *frigidaria* of the Porte d'Orée baths in Fréjus and the North Baths at Cimiez, where they were apparently used for structural purposes to reduce the lateral thrusts on the walls. But otherwise, these voussoirs seem to have provided a kind of prefabricated method of building vaulted baths quickly, a type of bath building "kit" that developed during periods of rapid urbanization and was then adopted in the subsequent phase of the expansion of villa culture.

The armchair voussoirs continued to be used into Late Antiquity, when they appeared in a second wave of late antique bath construction. The greatest concentrations were in southwest Gaul comprising Aquitania and the fringes of western Narbonensis and in northwest Iberia, mainly Gallaecia. Aquitania, in particular, was extraordinarily dense with opulent late antique villas, some of which employed armchair voussoir vaults in newly built or renovated baths. As shown on the distribution map in Figure 113, many of the examples come from undated contexts, so it is impossible to determine whether they were part of an earlier bath or were added during late antique renovations. In at least five cases, they come from securely dated late antique villa contexts,[93] one of which is the well-known villa at Valentine, so the technique clearly continued to be part of the building vocabulary.

Villa life in Aquitania during Late Antiquity has been carefully examined via archaeological, literary, and prosopographical studies. Connecting the villas to particular families is rarely possible, but we have a clear overview of the people inhabiting the area and what they were doing.[94] Bordeaux, in particular, as a diocese capital, became a center of learning and a place that attracted those aspiring to become part of the imperial court. The fourth-century rhetor, Ausonius of Bordeaux, is the most famous example of the rise of a late antique aristocrat through his connections to the emperor, Valentinian I.[95] This area of southwest Gaul became one of the most densely packed areas for monumentalized villas owned by men such as Ausonius, who benefited from the new opportunities offered under Diocletian's reorganization of the provincial governing structure (see Chapter 1).[96]



113. Distribution map of villa baths employing armchair voussoirs. Note the cluster of late Roman examples in Gallaecia.

The concentration of armchair voussoirs in northwest Iberia is more surprising because, in contrast to Aquitania, there had not been a strong villa presence in this area earlier (Fig. 113).[97] Moreover, it was generally seen as a marginal zone that adhered to local traditions and was slow to adopt the Roman lifestyle.[98] Strabo, writing soon after the conquest of Hispania by Augustus, was not enamored of the people of Spain in general, but he shows particular disdain for both the land and the people (the Cantabrians) of the northwest. He notes that the isolated position and mountainous landscape led to uncivilized people with savage manners, including the practice of washing their teeth with urine![99] How and why did this outpost of the civilized world come to have so many late antique villas? The answer may lie with other noteworthy aspects of the newly created province of Gallaecia. Northwest Spain had housed the Legio VII Gemina at León (ancient Legio) since Flavian times in order to oversee the gold extraction in the region. However, state-controlled mining ended by the mid-third century, so the continued military presence there at León, Lugo (ancient Lucus Augusti), and A Coruña (ancient Brigantium), as attested by the *Notitia Dignitatum* (c. 400 CE), has presented a conundrum.[100] Smaller scale privatized mining continued farther west around Lugo, apparently under the large landowners in the area, who may have relied on the military for protection.[101]

That the imperial authorities were interested in the northwest corner of Iberia is exemplified by the intense road repair attested by more than one hundred milestones dating from the mid-third into the fourth century.[102] Portugal and northern Spain also witnessed the building of defensive walls for more than twenty cities, including Lugo, Braga, and possibly Chaves.[103] The military presence, the road repair, and the construction of fortification walls must all have been related in some way to the imperial strategy for this region. Various explanations have been put forth: continued small-scale mining activity, recruitment of troops for units in Britain and Germany, or supplying the *annona militaris*, all of which have some merit but little evidence.[104] Most recently, K. Bowes has focused on the role of tax collection and the economic stimulus created by a burgeoning bureaucracy to explain the proliferation of roads, city walls, and villas. Braga (ancient Bracara Augusta), the provincial capital, would have housed a variety of elite officials, both military and civilian. Other fortified cities, such as Lugo and León, were home to military units, which could have provided military contracts for landowners. In the absence of a dense network of cities, the *pars urbana* of the villas would have provided the main venue for social competition.[105] Thus the concentration of the armchair voussoirs in the villa baths of Gallaecia can probably be seen as a byproduct of the larger social changes at work during Late Antiquity.

Ultimately the armchair voussoirs provide a glimpse into the process of urbanization and the subsequent villa culture as it developed in the western empire, particularly during the first century CE and again in the fourth century. Factors affecting the spread of the technology include adoption of a bathing culture and the aqueduct building that came with it, agricultural development and increased amphora production resulting in expanded terracotta production, the role of the military both in brick and roof tile production and in constructing baths, and the rise of villa culture that developed first with the wealth accompanying urbanization and then with the renaissance that came later with the new provincial governing system initiated by Diocletian. Very few of the structures employing armchair voussoirs are particularly noteworthy for their size or for pushing any structural boundaries, yet the story they tell about the development of the western half of the empire is a broad one that incorporates many social and economic trends over time.

8

VAULT BEHAVIOR AND STRUCTURAL FORM

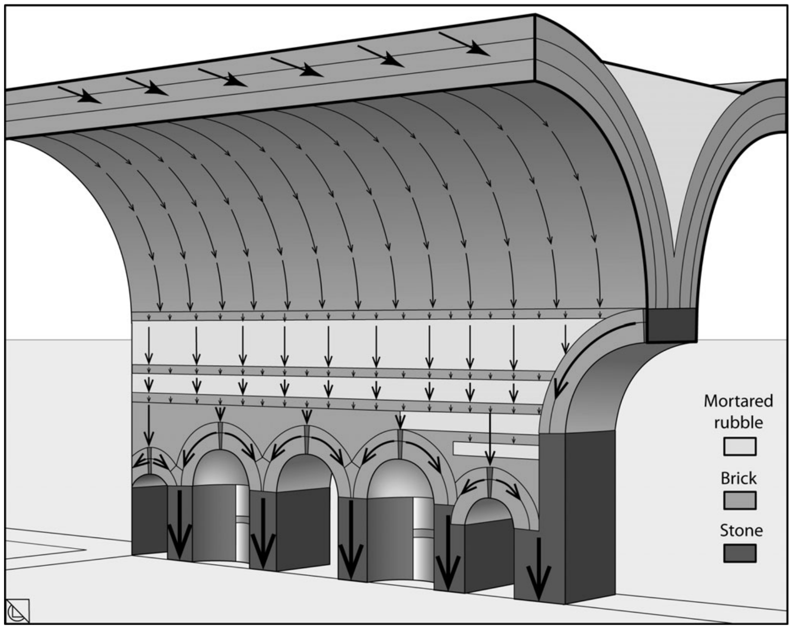
In this chapter I use a series of case studies to explore the structural efficacy of some of the vaulting techniques discussed in previous chapters and the impact they had on individual monuments. Structural efficacy is only one factor governing the decision to use a particular vaulting technique, but by understanding the structural advantages (or disadvantages), one can better weigh them against economic, aesthetic, and social factors as influences on the choice of technique. As noted at the beginning of this book, there are two main issues in assessing the stability of a structure: (1) the ability of the vault to support itself and (2) the ability of the abutments to resist the lateral thrust imposed by the vault. I examined the first issue in Chapter 1, and here I focus on the second one. First, I look at how the builders used various types of structural systems to manage vault behavior. I then introduce thrust line analysis (also called the funicular polygon method), which provides a graphical method of determining how a vault interacts with its abutments and in turn highlights the importance of structural form in guaranteeing a building's stability. Finally, I present a series of case studies that use thrust line analysis as a way to answer specific questions about the vaulting techniques and the monuments that employ them.

VAULTS AS PART OF STRUCTURAL SYSTEMS

Vaults are inevitably part of a greater whole involving foundations, walls, columns, and door and window openings, which are all juxtaposed to create a structural system. Typically, the larger the structure, the more complex the system. Many of the structures examined in this study are relatively small and have fairly simple structural systems with barrel vaults running side by side so that the lateral thrusts are counterbalanced. Among the most complex structures are the bath buildings of western Asia Minor, which have some of the largest vaults outside of Italy (WebCat. 1). One of the largest is the Bath-Gymnasium complex at Sardis, with its *caldarium* vault spanning 18.2 m. Because it is one of the few of this group of baths to have been thoroughly studied, thanks to the detailed work by F. Yegül,[1] a closer look at its structural principles provides some context for how the vaults fit into the overall structural system.

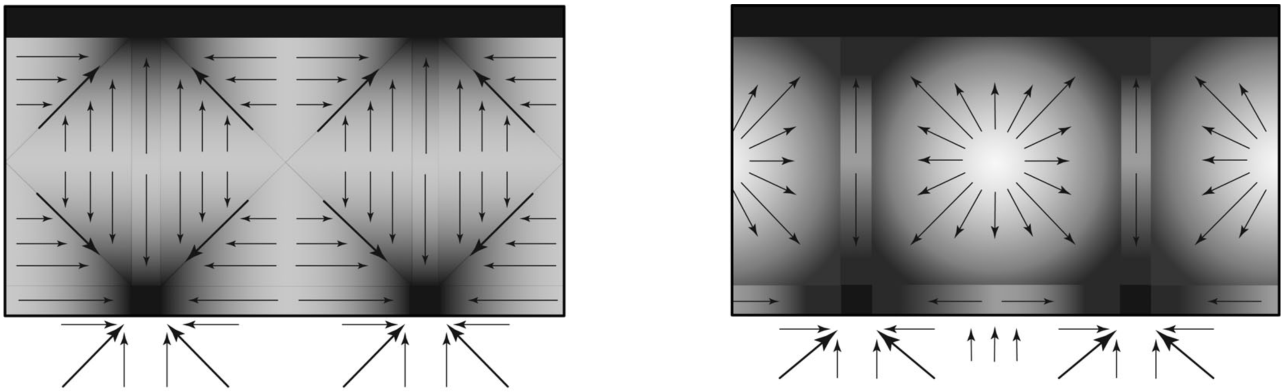
The Sardis Bath-Gymnasium complex (second century CE) was for the most part conceived as a

Catalogs (WebCat.) and color figures (WebFig.) can be downloaded at www.cambridge.org/vaulting



114. Bath-Gymnasium complex at Sardis, Turkey (second century CE). Drawing of *frigidarium* vault showing the compressive forces flowing through the structure in relation to the hierarchy of materials used (modified from Yegül 1986: fig. 201).

type of armature employing a hierarchy of materials (Fig. 114). The main load-bearing elements at ground level are ashlar piers (either solid block or mortar filled) connected by brick arches. The spaces under the arches consist of either niches or partition walls built of mortared rubble with occasional horizontal bands of brick. They are not bonded to the ashlar piers or to the arches and appear to have had little structural function. In low rooms, the brick arches support the springing of the vault, whereas in taller rooms there is a stretch of mortared rubble walling with brick bands above the arches. In both cases, the weight of the vaults is transferred via the arches to the system of ashlar piers at ground level. Yegül observed that the stone-facing blocks between the bands of brick courses were carefully placed and adhered to a pattern in which the larger blocks were placed at the bottom and smaller slab-like pieces at the top to form the base for the brick bands. The core, in contrast, was much less carefully laid, with random river stones and pebbles mixed with relatively little mortar, leaving air gaps within the mix (unlike the *opus caementicium* at Rome, which was carefully tamped to eliminate any gaps). The vaults of the superstructure that are in situ or were excavated where they fell consist of radially laid brick shells with their spandrels filled with the crude mortared rubble mix. The brick shell was evidently conceived as the structural unit transferring the forces to the walls, with the mortared rubble acting as inert surcharge. The large number of roof tiles found in the excavation led Yegül to propose that the vaults were covered by tiled wooden roof structures. The construction of the vault of the drains also demonstrates a hierarchy of materials, with the sections running through foundations built of stone voussoirs and the sections running under the floor made of radially laid mortared rubble.[2] At Sardis, in spite of what may seem like the careless execution of some of the mortared rubble, the builders were making well-informed decisions with regard to



115. Diagram showing the pattern of lateral forces in a portico with cross vaults (left) and one covered with sail vaults (right).

materials – they retained the stone armature as a means of focusing loads to particular points within the structure, which in turn allowed for a more efficient use of materials in non-load-bearing zones.

A different type of structural system can be seen in vaulted porticos, where the structural challenge is not related to large spans in massive monuments but rather to the delicate nature of the support structure in relatively small monuments. The vaulted portico, with either cross vaults or sail vaults, is a phenomenon that first appeared in the architecture of Asia Minor and North Africa during the second century. It was employed earlier in Rome, particularly in the imperial thermae and at Hadrian's Villa, but there it typically supported barrel vaults of *opus caementicium* on flat architraves that employed metal bars to resist the lateral thrusts of the vaults.[3] The builders outside Italy developed a different means of dealing with vaulted porticos; in North Africa they employed mortared rubble cross vaults laid on a permanent centering of vaulting tubes, whereas in Asia Minor they used brick sail vaults. Porticoes became fashionable in response to the increased availability of colored marble column shafts in the second century.[4] Although not all porticoes employed colored marble, the increased desirability of porticoes in general was no doubt affected by those that did. The new techniques of building vaults with vaulting tubes and brick shells provided the builders in the provinces a way to incorporate vaults into porticoes of both private and public structures.

In Africa Proconsularis, the use of vaulting tubes provided a very efficient type of centering that eliminated complex wooden structures needed to form the cross vaults. The vaulting tubes also provided the structural advantage of creating a stiff permanent formwork that supported the mortared rubble infill above. In all examples where the infill remains, the rubble has been laid radially like the voussoirs in an arch, presumably to compensate for the deadweight on the tube shell while the mortar gained its strength (Figs. 15, 77, WebFig. 24). The structural behavior of a cross vault was also well suited to a columned portico because the horizontal thrusts act along the diagonals of the vault, such that they are partially canceled by the thrusts from the neighboring vault (Fig. 115), unlike a barrel vault where the colonnade would have to resist the full force of the lateral thrust. The vaulted porticoes in North Africa are usually small, around 2 m in span, so the lateral thrusts were not so great, and they generally have a maximum of four bays on any side so that stability is not a problem.

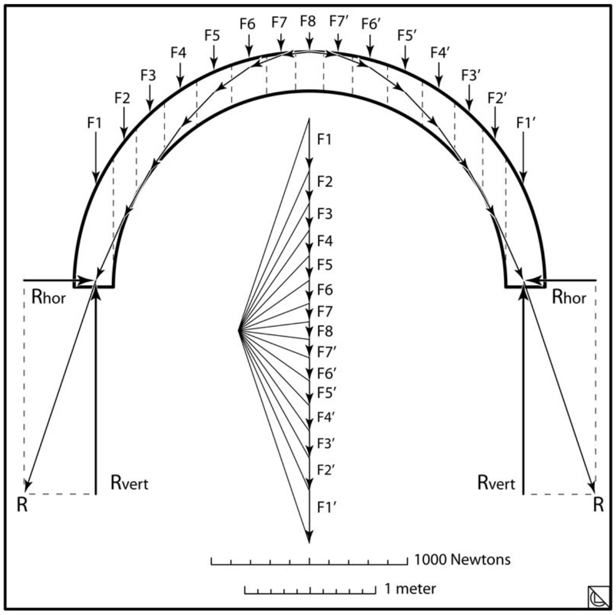
A notable exception occurs at Dougga at the Sanctuary of Juno Caelestis (222–235 CE), which has a twenty-seven-bay portico with a span of 3.5 m.[5] Along the back wall of the annular portico are the semicircular rebates (7–14 cm deep) typical of cross vaults built with vaulting tubes (Fig. 82).[6] In this case, the annular form of the portico provides an inherent structural advantage for two reasons. First, the inner side of the trapezoidal vaulted bays are naturally narrower than the outer side, which brings the columns at the inner corner of each bay closer together, increasing the stability. Second the semicircular form of the portico as a whole acts as a horizontal arch that provides additional resistance to the lateral thrusts on the columns. This example demonstrates a sophisticated understanding of the way in which form and technique can be used together to increase the stability of the structural system.

In Asia Minor, vaulted porticos are attested at two sites: the two Terrace Houses at Ephesus and the West Mausoleum at Side. The one at Side is the most interesting from a structural perspective. It employs a series of brick sail vaults (3.85 m span) along two sides of a funerary complex surrounding a temple tomb (Fig. 53). In comparison to a cross vault, a sail vault distributes the lateral thrust more evenly around the shallow, saucer-like dome before channeling the load to the columns via the pendentives at the corners. As with a series of cross vaults, part of the lateral thrust is canceled out by the neighboring vaults; however, the domical nature of the sail vault results in some outward thrust distributed between the corner supports (Fig. 115). This characteristic of the sail vault may have determined the unusual design decision for the portico. The front face of each vaulted bay is supported by two arches resting on three columns, except for the end and central bays, which are contracted and supported by a single arch (Figs. 52, 53). In addition to the aesthetic appeal of giving a greater presence to the end and central bays by eliminating the central column, the division of the intermediate bays into two parts also provided a structural advantage. The use of two arches per bay not only increased the number of supports but also added mass to the abutment in the form of the spandrels between the arches over the columns, which in turn acted as surcharge to counteract the outward thrust of the shallow dome-like crown. An alternative configuration for the portico would have been to use cross vaults, which would have required significantly less volume than similarly sized sail vaults but much more complex wooden centering.[7] The designer and builders again exhibited a keen understanding of the structural system as whole and made sophisticated choices in terms of structural form, mass, and geometry.

The vaulted porticos in North Africa and Asia Minor do not rival those in Rome, which reached spans of six to seven meters, nor did they need to given the contexts, but they demonstrate the creative application of new techniques used in different ways to respond to local personal and civic aspirations.

THRUST LINE ANALYSIS AS A TOOL FOR EVALUATING STRUCTURAL BEHAVIOR

In Chapter 1, I discussed a quick and easy method for determining whether a barrel vault or dome can support itself using the ratio of arch thickness to free span. However, determining whether the abutments can support the lateral thrust imposed by the vault is a more complex task. Just because the vault can support itself does not mean that the structure as a whole is stable. Thrust line analysis provides a means to trace the path of compressive forces from the vault down to the foundations (i.e., the line of thrust). In my previous book on concrete vaulting I explain the history of this method and provide a detailed explanation for how to apply it to a barrel vault,[8] so here I offer only an overview to prepare the reader for the following discussions where thrust line analysis is applied.



116. Example of a funicular polygon diagram used in graphic thrust line analysis.

The line of thrust in a vault is a graphic representation of the internal line of compressive forces acting within the structure. The method of establishing it is based on the principle that each voussoir in an arch has a certain weight (= mass × gravitational force) that can be represented on a section drawing of the structure by a vector (i.e., a line drawn to a certain scale representing the magnitude of a force). Heavier blocks are represented by comparatively longer vectors. The voussoir is not only pushing down due to its weight but is also being held in place by equal and opposite horizontal forces from its neighboring voussoirs. This compressive pressure is what keeps all the pieces together. The internal forces between the blocks can also be represented by scaled vectors. Each voussoir can be represented by a vertical and horizontal vector that together form a composite vector representing a force pushing diagonally down and out toward the abutment (e.g., R_{vert} and R_{hor} are the two components of R on Fig. 116). The thrust line is the path created when all these composite vectors, each acting through the center of gravity of its voussoir, are placed end to end. If the resulting thrust line stays within the masonry of the structure along its entire trajectory to ground level, the structure is stable. If the line goes outside the masonry in the abutment, it means that the horizontal components represented by the thrust line are pushing out with more force than the weight of the abutment can resist, and the thrust of the vault will potentially cause the abutment to tip over.

Thrust line analysis assumes that the structure has no resistance to tension; thus it is a conservative method because some combinations of stone, brick, and mortar do have a limited resistance to tensile forces. It is fundamentally a way of evaluating the equilibrium of a structure by comparing the weights of its different parts in relation to its geometry. The point is to assess if the materials are subject to tension. Ideally, in a masonry structure the weights of the different parts work together to create a balanced whole that does not *require* tensile resistance to ensure stability. If the thrust line does not stay within the masonry, but the structure clearly stood at some point, then we must look for ways in which it could have resisted the tensile forces. In this chapter, I apply thrust line analysis to a series of case studies to evaluate the efficacy of various vaulting techniques and to assess the stability of particular structures.

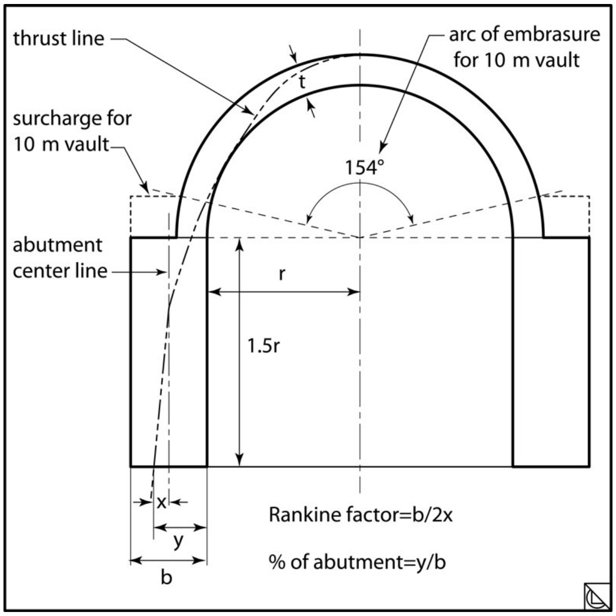
Today we can use modern analytical methods to answer questions about structural stability, but what analytical tools were available to the Roman architects, builders, and engineers who designed and built the structures? In spite of their mastery of vaulted construction, there is no evidence that the Romans ever had the means to calculate the magnitude of vault thrusts in the way we do today; however, they did understand the principle of balancing mass and geometry. During the third century BCE, Archimedes had discovered the concept of the center of gravity (which is the point at which an object will balance as if the whole of its weight is concentrated at that point). This was related to his investigation of the principle of the lever for moving masses. The ancient mathematicians and engineers never translated this mathematical and geometrical knowledge into a method for calculating forces. This knowledge only came in the sixteenth century with the Enlightenment when the theoretical concepts of forces, vectors, and stresses were introduced. The vector allowed for the visual representation of a force (Figs. 4, 115), which in turn allowed geometric principles to be used to study structural issues.[9] We do not know exactly how the Roman builders approached the design of their vaulted structures, but they likely relied on proportional and geometric rules of thumb based on their understanding of form and mass.[10] However they did it, they seemed to have had good judgment, but we encounter some examples where the structures teetered on the borderline of stability, such as the cult building at Argos, and others where problems occurred due to insufficient buttressing, such as the Sacred Spring at Bath. The true disasters presumably did not survive to tell their story![11]

CASE STUDY 1: HOLLOW VOUSSOIRS VS. SOLID BRICK – A COMPARISON OF STRUCTURAL EFFICACY

A number of the vaulting methods examined in this study served to lighten the vault and reduce the lateral thrust on the abutments. However, many of the vaults were quite small, with spans of three to five meters. Given such modest spans, a question arises regarding the efficacy of each method – at what span does a particular vaulting technique become an effective means of increasing structural stability? This is a question that thrust line analysis is well suited to answer. By designing a series of models that use certain constants shared between them, we can isolate the relationship between the chosen technique and the effect that it has on the required wall thickness to maintain stability. Using these models I compared solid brick vaulting (the heaviest of the terracotta techniques) with hollow voussoir vaulting (the lightest). In each case, a typically sized tile creates an arch with a 30 cm thickness, which approximates the Roman foot (RF).[12] In terms of wall thickness, Roman builders often used modules based on the Roman foot (RF), so I chose thicknesses of 60 cm, 75 cm, 90 cm, 120 cm, and 150 cm. For wall height, I used a ratio of 1.5 times the arch radius. This choice is based on the average of two examples for which the ratio of arch radius to wall height is known: that of the cult room (A1) of the cult complex at Argos (1:1.3) and of the *frigidarium* of the North Baths at Cimiez (1:1.8). The models include a comparison of three different spans:

1) 3 m, which gives an arch thickness to span ratio of 1:10 and is close to the median span of the hollow voussoir vaults for which the span is known (Fig. 97)
2) 5.25 m, which gives an arch thickness to span ratio of 1:17.5, only slightly lower than the theoretical maximum of 1:17.6 for a 180° degree arch
3) 10 m, which approximates the largest spans documented using hollow voussoirs of this size. Because a semicircular arch of 30 cm is no longer self-supporting at this span, the arc of embrasure is reduced to the maximum possible of 154° by adding surcharge above the haunch.[13]

The exercise is theoretical in that I am simply testing for the ability of the abutment to support barrel vaults of different weights and spans. I assume no surcharge (except that needed for arch stability), when in reality, even the smallest vault would have had some additional weight in the spandrels. To compare the results, I used two indicators. The first is based on a principle set forth by W. Rankine in the nineteenth century for determining a factor of safety based on the thrust line.[14] He stated that to remain "safe" the thrust line



117. Drawing showing the parameters for the models set up to compare the structural effect of different sized vaults employing hollow voussoirs.

should stay within the middle third of its abutment everywhere so that tension does not develop due to the applied thrust of the vault. To discuss the results of the following analyses, I used a formula to determine the "Rankine factor" as illustrated in Figure 117. A Rankine factor of 1 or below indicates the point at which the abutment can no longer remain standing, and a Rankine factor of 3 or above indicates that the thrust line falls within the middle third of the abutment. For Rankine factors between 1 and 3 the abutment can stand, but as it approaches 1, the structure's stability becomes more precarious, and external factors such as foundation subsidence, slippage between stones, or even horizontal wind loads could cause failure. I also used a second indicator based on the same principle, but one that is perhaps easier to conceptualize. The closer the thrust line gets to the outer edge of the wall, the closer the structure comes to collapse, so a measure of the percentage of the abutment "used" gives an idea of how close the structure is to failure, with failure occurring when 100 percent of the abutment is used. Percentages less than 67 percent are considered safe according to Rankine's rule. These indicators are simply two different methods of making numerical comparisons that can be summarized more easily than looking at a series of small-scale thrust line drawings. For the present discussion, the two methods are always applied at the base of the abutment, where stability is most critical.

The results of the comparison of the 3 m arches indicate that a 60 cm thick wall would be sufficient for both the hollow voussoir and the brick arches. The hollow voussoir arch has a very high Rankine factor of 4.1 and uses only 62 percent of the pier base, whereas the solid arch has a Rankine factor of 1.4 and uses 85 percent of the pier base. The solid arch has a smaller margin of safety, but both structures are stable. Because Roman structural walls were rarely ever thinner than 60 cm (2 RF), this analysis demonstrates that using the hollow voussoirs in place of solid brick has a negligible effect on the stability of the structure at this scale. Given that a vast majority of the vaults built with hollow voussoirs fall in the range of three meters (Fig. 97), the builders were unlikely to have been using them primarily for structural reasons, except for special occasions.

At a span of 5.25 m, the difference between the behavior of the two different structures becomes more tangible. The hollow voussoir vault remains stable on a 60 cm thick wall with a Rankine factor of 1.8 using 78 percent of the pier base, so it has a similar margin of safety as the 3 m solid brick vault. The 5.25 m solid brick vault, in contrast, requires a 90 cm wall, which would give it a Rankine factor of 1.3 using 89 percent of its pier base. Clearly the weight difference begins to have an effect at this span. In fact, we can see on the chart of hollow voussoir vault spans (Fig. 97) that there are very few with spans greater than five meters, and most of those are in the 10 m range.

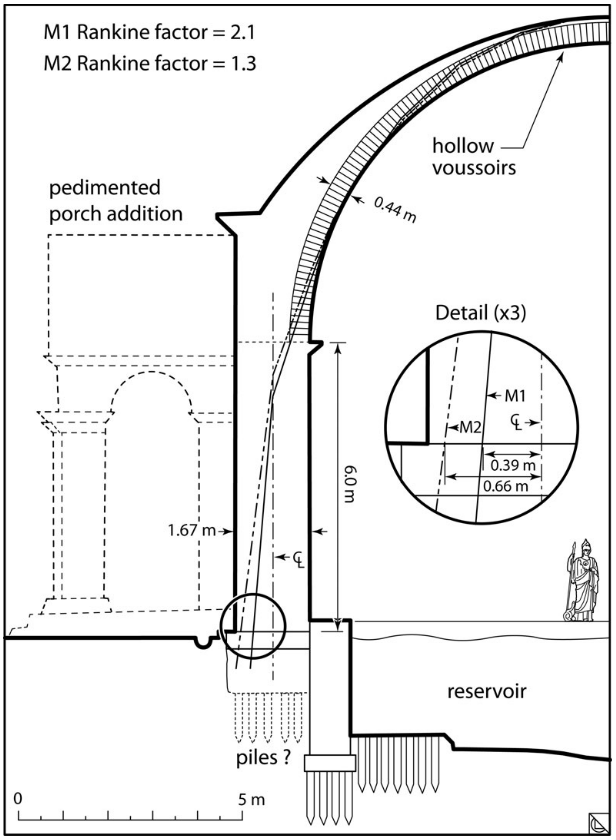
At ten meters, the structural effect of using the hollow voussoirs is much more substantial. With the hollow voussoirs, a wall thickness of 90 cm (together with the requisite haunch fill) is sufficient to maintain stability with a Rankine factor of 1.5 using 84 percent of its pier base. The solid brick vault requires a wall thickness of 150 cm with a Rankine factor of 1.6 using 82 percent of its pier base. As can be seen in these analyses, the use of the hollow voussoirs made a substantial difference in the required wall thickness at such large spans, whereas it clearly had very little effect on the wall thicknesses for the vaults with small spans.

A similar analysis could be done for armchair voussoir vaults, the weight of which would lie somewhere between the hollow voussoir vaults and the solid brick ones. For armchair voussoir vaults, the median span (when it is known) is 4.8 m, but because this figure does not include numerous villa contexts where the spans are not recorded and were inevitably at the smaller end of the scale, the actual figure is probably lower. For very large vaults, both the hollow voussoirs and the armchair voussoirs appear to have been used to reduce the outward thrust on the support structure, but for the vast majority of the smaller structures both these techniques would have had minimal effect on the overall structural stability.

CASE STUDY 2: THE SANCTUARY OF SULIS MINERVA AT BATH

At the Sanctuary of Sulis Minerva in Bath, two vaults employing hollow voussoirs are particularly notable: the one covering the Sacred Spring, which is the largest barrel vault in Britain at 13.6 m, and the one covering the Great Bath, which is smaller at 10.5 m but employs a more sophisticated structural system. The sanctuary is located at a hot spring that had been sacred even before the arrival of the Romans. This geological context also created challenges for the builders because of the unstable and waterlogged nature of the site. They went to elaborate means to contain the Sacred Spring within a piled foundation so they could build on the surrounding terrain.[15] When the sanctuary was originally built in the last quarter of the first century CE, the Sacred Spring was open to the air, and the Great Bath was covered by a wooden roof. Later, the complex underwent a renovation whereby the Sacred Spring was enclosed in a vaulted room and the wooden roof of the Great Bath was replaced with a vaulted one (WebFig. 33 [plan]).[16] The only dating evidence comes from a Hadrianic coin found mortared to one of the strengthening piers added to the Great Bath when the vault was built.[17] Cunliffe gives a tentative dating of the late second/early third century CE for the renovation of both the Sacred Spring and the Great Bath.[18] This would place it during the reign of Septimius Severus when numerous other baths, often associated with legionary forts, were renovated on the occasion of his visit to the province. The examples at Bath are informative from a structural point of view because the use of hollow voussoirs could not have been for heating as neither vault covers a room with a hypocaust.

The vaulted structure covering the Sacred Spring apparently ran into stability problems within a few generations of construction because buttressing elements, including a quadrifrons porch, were added to the north support wall some time during the middle of the third century (Fig. 98). The pattern of the excavated remains indicate that the north wall eventually collapsed outward – parts of the north haunch were found to the north of the enclosure, and the main part of the vault was excavated where it fell in the middle of the enclosure.[19] A thrust line analysis can be employed to ask three questions: How effective was the use of the hollow voussoirs in maintaining stability? What was the maximum possible height of the original support walls? What was the likely cause of the collapse? To answer these questions, I created

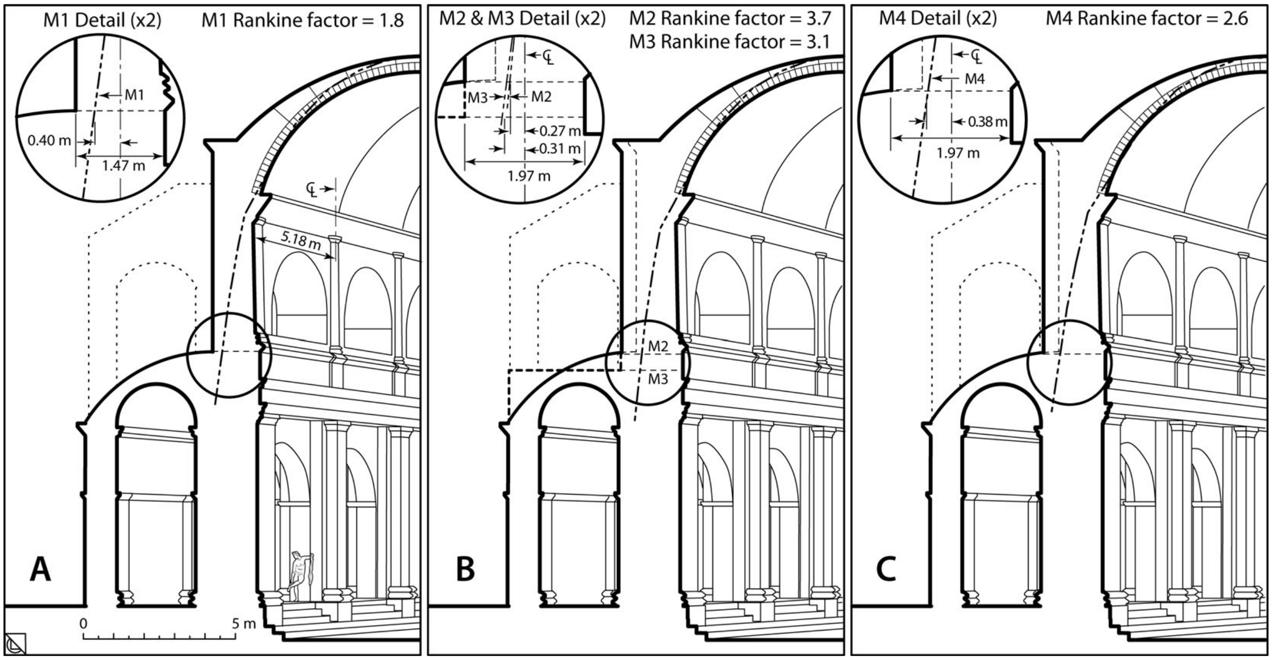


118. Sanctuary of Sulis Minerva at Bath, England. Thrust line analyses of the hollow voussoir vault of the Sacred Spring. Model 1 (M1) with vault of hollow voussoirs covered by mortared rubble. Model 2 (M2) with (theoretical) solid mortared rubble vaults.

two series of models, one with a hollow voussoir vault with a rubble fill and the other with a solid mortared rubble vault (Fig. 118), and then tested the thrust line at different wall heights. For all the models, I use 44 cm tall hollow voussoirs (as documented from the excavations) and assume that the mortared rubble of the walls and vault fill weighs 2,000 kg/m^3 and the terracotta 1,700 kg/m^3. The original height of the walls is not known, so for Model 1 (M1), I start with the most conservative estimate of six meters, which would put the spring of the vault near the bottom of the pediment of the quadrifrons porch.[20] Model 2 (M2) has a solid vault of mortared rubble.

The results for Model 1 shows that the hollow voussoir vault would have a Rankine factor of 2.1 and use 73 percent of its wall thickness, whereas Model 2 with the solid mortared rubble vault would have a Rankine factor of 1.3 and use 90 percent of its wall thickness. The solid vault would theoretically be stable, but clearly, even at this low 6 m wall height, the hollow voussoirs made a significant difference in the stability of the structure. For Model 3 (not illustrated), I test the hollow voussoir vault on a 10 m high wall, which would have a Rankine factor of 1.3 and use 90 percent of its wall thickness, whereas Model 4 (not illustrated), a solid rubble vault on a 10 m high wall, surpasses its failure point with a Rankine factor of 0.9 and the thrust line would have gone outside of the wall. These results indicate that the use of the hollow voussoirs allowed for considerably more flexibility in wall height than a solid vault would have. They also show that, even in the best case scenario for the hollow voussoir vault, its Rankine factor does not come close to the modern preferred level of safety of three, and the thrust line falls in the outer third of the abutment. An additional result is that the weight on the foundation is unevenly concentrated toward the outer edge, and in a marshy zone such as this, foundation subsidence was a real danger.[21] This combination of factors probably lead to cracking and the outward tilt of the wall, which eventually prompted the addition of the buttressing elements. Additional buttressing would help support the wall in two ways: by providing a load path for the thrust line to exit the original supporting walls and by adding additional resistance to overturning due to the self-weight of the buttress.

The second large vault at Bath using the hollow voussoirs was the one added to cover the Great Bath. The original structure consisted of a large central area flanked by side aisles, all covered with timber roofing. To support the new vault over the central space, the builders increased the thickness of the original piers from 0.80 m to 2.00 m by adding to both sides. Much of the history and reconstruction of the Great



119. Sanctuary of Sulis Minerva at Bath, England. Thrust line analysis of the hollow voussoir vault of the Great Bath A: Model 1 with thin upper wall. B: Models 2 (with curved extrados over aisle) and 3 (with flat extrados over aisle) with thicker upper wall. C: Model 4 with (theoretical) solid mortared rubble vault on the thicker upper wall.

Bath are based on finds from Cunliffe's excavations at the site in the 1960s. The evidence for a clerestory is a fragment of an engaged column, which must have belonged to an upper order above the enlarged pilasters below. Between these engaged columns, the excavators reconstructed semicircular clerestory windows that would have allowed light into the space.[22] The aisle roofing of hollow voussoirs is attested by the fallen fragments found in nineteenth-century excavations.[23] One uncomfortable aspect of the excavators' reconstruction is that the aisles seem too low to provide effective resistance to the lateral thrusts of the main vault (Fig. 119A). By examining the structure with a thrust line analysis of various possible configurations, we can come to more definitive conclusions about the viable alternatives.

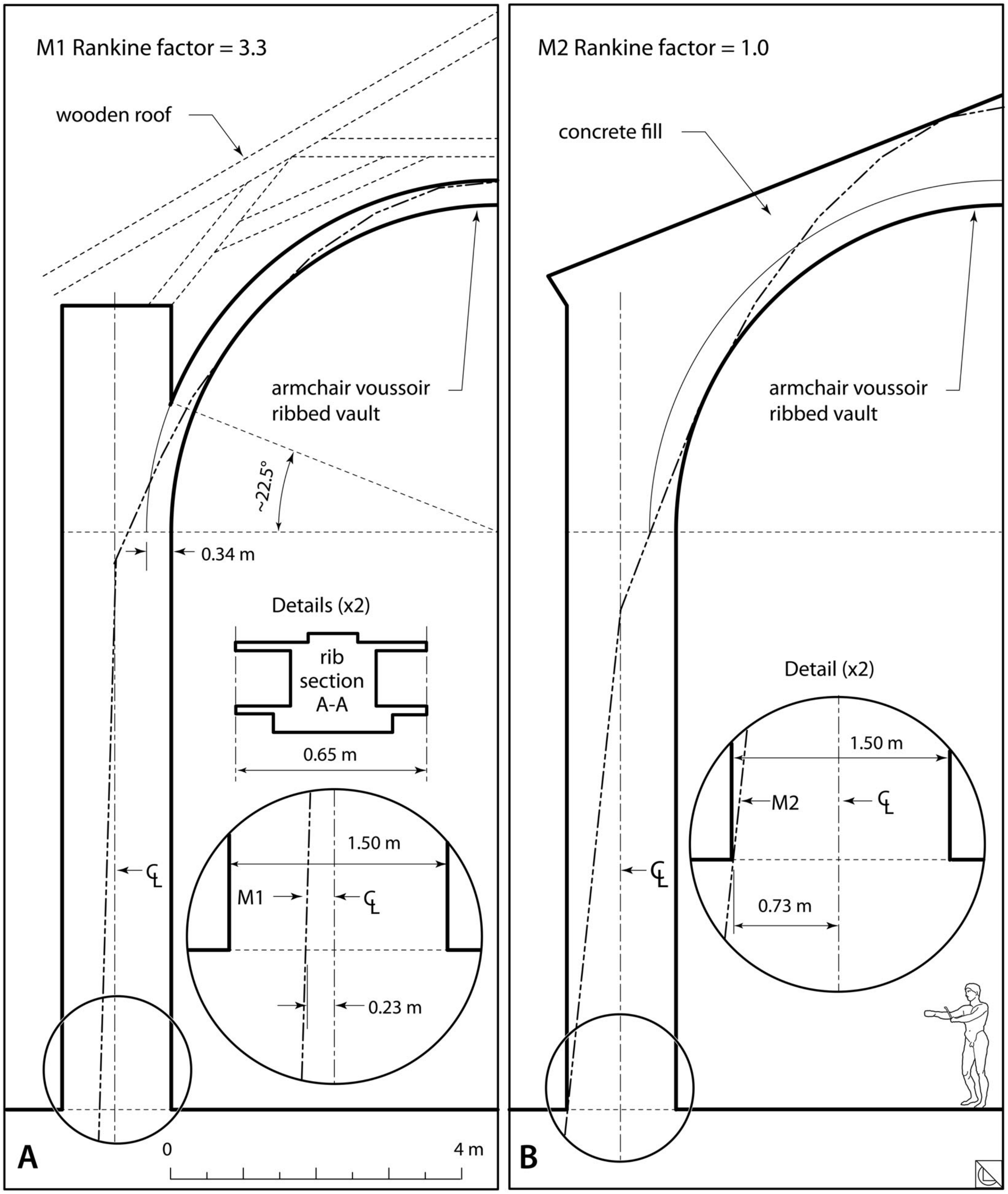
To test the stability of the excavators' reconstruction, I made a thrust line analysis of the main vault using 30 cm tall hollow voussoirs, many of which are still located in the on-site storerooms. To account for the large openings of the clerestory windows, I calculated the thrust from the vault of a single bay (5.18 m long) supported on one of the piers with the engaged columns. In Model 1, the clerestory wall extends down to the top of the curved extrados of the aisle vault as reconstructed by the excavators (Fig. 119A). The results show that the Great Bath vault would have a Rankine factor of 1.8 and use 76 percent of its wall thickness – theoretically possible but without much margin of safety. Considering the wind loads that would affect the upper stories of the building, this configuration does not inspire confidence. A very simple modification is to increase the thickness of the clerestory wall so that its outer face aligns with the face of the ground-level pier. The fact that the builders increased both sides of the original piers suggests that this was done to support a thicker wall above. This thicker wall is tested in Model 2 with the resulting configuration improving to a Rankine factor of 3.7 using 64 percent of the wall thickness (Fig. 119B). In this case, no other buttressing would be required. The stability in Model 2 is enhanced by the reconstruction of the aisle vaults with a curved extrados that effectively reduces the freestanding height of the clerestory wall, but a more typical arrangement is to have a flat extrados, as in Model 3. The results of this configuration give a Rankine factor of 3.1 using 66 percent of the wall thickness (Fig. 119B). Thus both the curved and the flat options were viable. Theoretically both Models 2 and 3 could stand safety without external buttresses as long as the thicker clerestory wall was used. Nevertheless, without such a means of quantification, Roman builders may well have felt more confident with the buttresses.

Lastly, how much difference did using the hollow voussoirs make to the stability of the structure? To answer this, in Model 4, I substitute a solid mortared rubble vault onto Model 2 with its thicker clerestory wall (Fig. 119C). This configuration brings the Rankine factor down to 2.6 using 70 percent of the wall thickness. Compared to the very stable Rankine factor of 3.7 for the hollow voussoir vault in Model 2, the solid vault would have reduced the stability significantly but the structure would have stood nevertheless.

Both of the vaults examined from the Sanctuary of Sulis Minerva were audacious undertakings, largely because the builders were limited by preexisting conditions of earlier structures and unstable soil conditions. The vault over the Sacred Spring was particularly ambitious – not only was it the largest vault in Britain but it was also freestanding on one side and did not benefit from buttressing by other surrounding structures. Hollow voussoirs had been used in the city of Bath earlier (Chapter 6) and probably even in this bath complex, but their use in these two vaults is singular in both size and complexity. Whoever conceived of this renovation was trying to make a structural statement in this far corner of the empire.

CASE STUDY 3: THE NORTH BATHS AT CIMIEZ

The North Baths at Cimiez (ancient Cemenelum) are worthy of investigation because they are one of only two structures that employ armchair voussoirs in large-scale vaults, the other being the Porte d'Orée baths in Fréjus (ancient Forum Julii). In both baths, the technique is used in *frigidaria*, so like the hollow voussoir vaults at Bath, they could not have been heated. The Cimiez baths, however, are also significant for having the support walls substantially intact with traces of armchair voussoirs in situ, which allows for an accurate reconstruction of the wall height. One of the questions regarding armchair voussoir vaults is whether they were ever used as permanent centering for concrete vaults. The North Baths at Cimiez provide the only example for which any evidence has been cited for this configuration. In Chapter 6, I suggest that the "evidence" is largely due to a misunderstanding of the terms employed in the excavation report. The thrust line analysis provides a means of testing whether a concrete roof was structurally possible. For Model 1, I use the remains of the standing structure, which provides the span of the vault (9.0 m), the height of the springing (8.0), and the thickness of the ribs (0.34 m).[24] The preservation of the outer wall to a height (11.0 m) well above the springing of the vault also provides an important parameter for reconstructing both a trussed roof (Model 1, Fig. 120A) and a concrete roof (Model 2, Fig. 120B). The t:D ratio for the full semicircular rib is 1:26, but by constructing the ribs into recessed vertical grooves in the wall (Fig. 109), the builders effectively reduced the arc of embrasure from 180° to 135°. For Model 1, I calculated the thrust line based on a 0.65 m wide slice of the vault, which includes the full width of



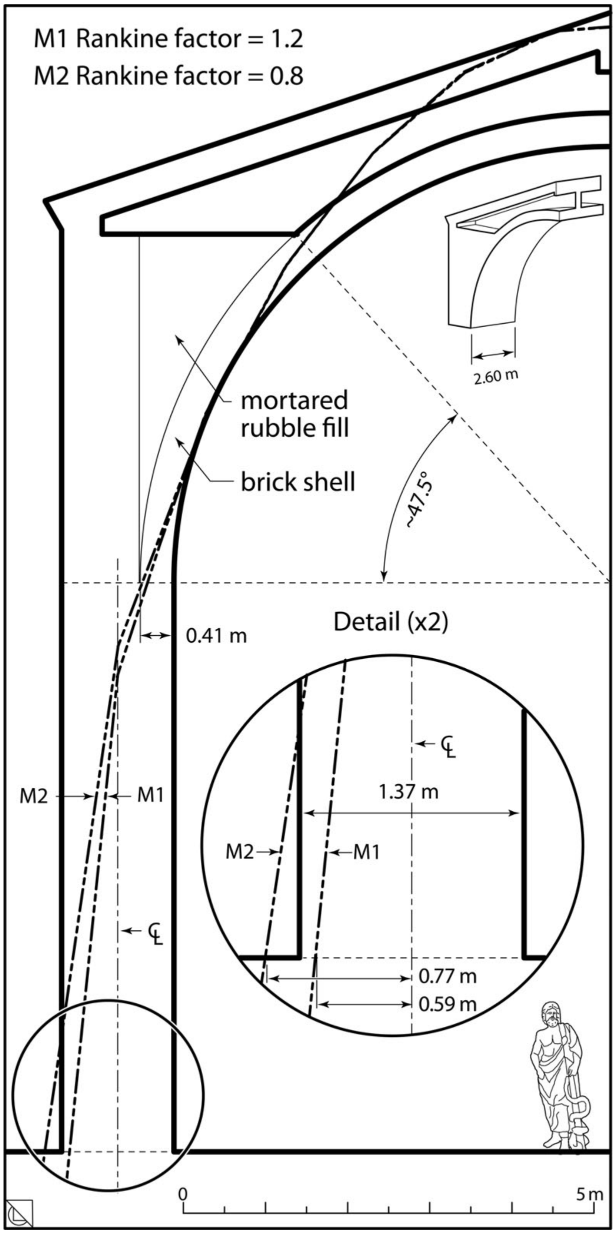
120. North Baths at Cimiez, France (ancient Cemenelum). Thrust line analysis of the *frigidarium* vault. A: Vault of armchair voussoirs assuming a wooden roof above. B: Vault of armchair voussoirs assuming a solid concrete vault above.

the rib plus half of the air channel on either side of it (Fig. 120A). This model yields a thrust line with a Rankine factor of 3.3 using 66 percent of the wall thickness, so it falls well within the middle third of the wall. In Model 2, with the armchair vault supporting a concrete fill above, the thrust line produces a Rankine factor that goes down to 1.0 and uses 99.7 percent of the wall thickness (i.e., it is at the point of failure). Clearly the structure could never have supported a concrete vault. Without this example, we are left with no evidence that the armchair voussoirs were ever used with concrete. If the armchair voussoirs were used primarily to create vaults covered by timber roofs as opposed to more solid concrete vaults, it is no surprise that none remains intact. As shown in Case Study 1 on the efficacy of hollow voussoirs, the use of lightweight vaults for small spans of about three meters would not have made a great difference in the stability of the structure, so the use of armchair vaults in numerous small villa baths was probably aimed more at material savings and ease of construction than at stabilizing the structure.

CASE STUDY 4: THE CULT COMPLEX AT ARGOS

The final case study is the large vault (10.6 m span) of room A1 at the cult complex at Argos, which employed a brick shell with approximately the same t:D ratio (1:26) as the Cimiez armchair vault. It is the most unusual vaulted structure in this study because the brick shell was combined with a hollow concrete gabled structure above. This roof consisted of a series of four walls running across the extrados of the brick shell, which in turn supported wooden formwork on which was laid the concrete slab forming the outer gable (Fig. 31). As with the Cimiez armchair vault, the brick shell was too thin to be self-supporting for the full 180°, so a mortared rubble fill was added above the haunch; this addition allowed the brick shell to spring about 47.5° above the impost, thereby reducing the arc of embrasure to about 85° (compare to that at Cimiez of 135°). The vault is preserved only as far as this fill, so the configuration at the crown is not known. I reconstructed the roof with a low rise and run of 1:4 based on the remains of part of the pediment visible along the back wall (Fig. 32). I also added a timber ridge beam spanning between the dividing walls, which would serve to eliminate any concrete mass resting on the crown of the vault.[25] The unusual design of the vault was clearly an attempt by the builders to reduce the weight of the upper part of the roof by creating the hollow spaces (discussed in Chapter 3). I used a thrust line analysis to evaluate the efficacy of this unique solution.

The thrust line in Model 1 is based on a 2.60 m slice of the building, which is the distance between the dividing walls on the roof (Fig. 121). The results show that the stability of the structure would have been very precarious. The thrust line produces a Rankine factor of 1.2 and uses 93 percent of the abutment thickness, which brings it dangerously close to the edge of the wall. It is worth noting that this model is based on a slightly different reconstruction from one I published earlier,[26] and I used different material weights to make it consistent with the other analyses presented here. Nevertheless, tinkering with these various factors in the analyses produced negligible differences in the thrust lines.[27] The analysis shows that this structure (as reconstructed) would stand in ideal conditions, but the low Rankine factor indicates that it would have had very little resistance to external factors, such as high wind loads, shifting foundations, or earthquake tremors. In Model 2, I test the same vault as if it were solid concrete, and it fails with a Rankine factor of 0.8. Thus the unusual configuration of the vault allowed the builders to create a stable structure on walls that would not have supported a typical concrete vault. In the end, the structure seems to have stood



121. Cult Complex (Theater Baths) at Argos, Greece. Thrust line analysis of the cult room (A1) showing results of Model 1 with hollow spaces above the vertical brick shell and Model 2 with a (theoretical) solid concrete vault above the vertical brick shell.

for at least a couple of centuries, if not more. At some point in the early Christian period, the complex was transformed into a monastery. The whole area has a destruction layer dating to the sixth century, which probably relates to the devastating earthquake in 552 CE. Exactly how long the vault of A1 stood is not clear.[28]

In addition to the hollow spaces built into the roof structure, another unusual aspect of the vault at Argos was the use of vertically laid brick in the shell, but the thrust line analysis does not take into account the material strengths or methods of construction – it only evaluates the relationship between form and mass. In reality, some masonry structures can resist low levels of tension. In Chapter 3, I introduced the idea of the "zipper effect" to describe the difference between the behavior of vaults built with vertical bricks compared to those built with radial bricks. Bricks have much greater resistance (30 kg/cm² (2.94 MPa)) to tensile stress than does mortar (about three to six times more than hydraulic mortars and even more for nonhydraulic mortars).[29] Any cracks that occur in a barrel vault run along the main axis, and in a radial brick vault, cracks can easily develop along a mortar joint – a straight path of least resistance – whereas in a vertical brick vault the bricks overlap to form the "zipper" pattern so that a crack would have to cross through the brick (as can be seen at Ephesus in Fig. 51, WebFig. 18). To put these numbers into perspective, we can compare them to other types of stress. For example, in the finite element analyses of the Pantheon by Mark and Hutchinson, they found levels of tensile stress could vary in their models from 0.5–4.9 kg/cm², but these figures were lower than the internal stresses of around 15 kg/cm² that could be caused by rain hitting the hot surface of concrete on a summer day.[30] In contrast, a material like iron, which is what the Romans used for tie bars, could resist tensile stresses of 800–1,000 kg/cm² before yielding. So the use of the vertical brick vaulting could have provided the Argos vault an added margin of safety, but it would not have provided the same level of stability as having thicker walls in the first place.

STRUCTURAL ANALYSIS AS AN AID TO CULTURAL UNDERSTANDING

In the preceding case studies, I isolated examples where applying one type of structural analysis can help provide insight into the choices made by designers and builders. The results of the analyses cannot always provide definitive answers for why structures were built the way they were, but they can help limit the possible answers and illustrate what sorts of problems the builders might have encountered during the process. They also help define the technology shelf from which builders in different regions had to choose. For example, the results of the comparative study of hollow voussoirs indicate that they would not have been useful as structural devices for vaults with spans up to about five meters because the difference in weight is typically not great enough to affect the standard wall thickness at this scale. This in turn illustrates why the large examples at Bath are extraordinary and puts the efforts of the renovation there in a new light. The other baths with large vaults, Canterbury and Wroxeter (Chapter 6), date to the early and mid-second century, respectively, and thus probably predated the ones at Bath. The fact that the hollow voussoirs had already been used for large-scale vaulting may explain how the architect at Bath came up with such a daring design – it was a culmination of at least a century of development. If the renovation at Bath did indeed occur as a result of Septimius Severus's visit to the province, it would have been part of a program of bath building and renovation that occurred at a time when imperial interest was focused on that province.

The results of the structural analyses from the North Baths at Cimiez are intriguing because that structure represented a sophisticated use and understanding of a technique that was otherwise used mainly for small vaults. The analysis demonstrates that in this case the technique had a clear *structural* advantage, as opposed to a *constructional* one. This is another building where the date has yet to be pinpointed, but if it could be dated with more accuracy, we would gain real insight into what was happening at this unusual complex of bath buildings. Likewise, the fact that the Porte d'Orée baths in Fréjus have a very similar sized *frigidarium* employing the same technique raises questions of the relationship between the two that have yet to be answered.

With regard to the cult complex at Argos, structural analysis is not needed to understand the unique nature of the vaulting system, but the results placing the thrust line at the limit of stability emphasize the experimental nature of the endeavor. In Chapter 3 and elsewhere,[31] I have argued for a Hadrianic date and follow J. Riethmüller's identification of the complex as a Sanctuary of Asclepius from its inception.[32] Such an interpretation would put it squarely in the period of Hadrian's cultural renewal of the cults of Old Greece and roughly contemporary with work occurring at the Sanctuary of Asclepius in Pergamum. Others, however, believe that it was built earlier.[33] From a cultural point of view, the emperor under which it was conceived is important because the use of such an extraordinary manner of building must have been part of some greater vision that warranted the innovation of using the vertical brick shell in such a singular manner.

In spite of the frustration presented by some of the dating problems encountered in these case studies, the results of the analyses emphasize the prestige value that these structures must have carried in their respective communities when they were built. They also highlight the creativity and sophistication of the vaulting solutions employed by builders outside of Rome.

9

VAULTING TECHNIQUES IN CONTEXT

My intention in this book has been to integrate building technology, specifically vaulting techniques, into larger discussions of economy, trade, and technological development. Architecture is an amalgam of various technological, economic, and social processes; thus, in modern times building is often seen as a barometer of economic well-being. However, studies of the ancient economy have many times overlooked building technology as an economic marker in favor of more strictly agricultural indicators, although this has begun to change.[1] Moreover, the architecture of the provinces, particularly the western ones, has been viewed with an eye toward its similarity with Italic prototypes rather than its originality and its contributions to technological advancement. In contrast, by tracing the diffusion of the vaulting techniques in this study (maps in Figs. 9, 18, 42, 66, 87, 102), we see that the provinces were rich in original ideas, though there is often a clear divide between the techniques used in the East versus those used in the West.

The results of this study emphasize the active role of local builders and craftsmen as agents of innovation. Architects no doubt played an important part in the design of innovative structures, especially large public ones, but there were probably many "design builders" (as we would call them today) who were creative craftsmen specializing in building and supplying the materials for small projects. Some of the innovations can be related directly to ideas that developed in terracotta workshops rather than on the design board of the architect. Nevertheless, the innovations and their diffusion occurred within an imperial system that generated the contexts ripe for such creativity, yet very few were initially employed in imperially sponsored structures. Most of the vaulting techniques discussed here were never employed in Rome, and if they were, as in the case of the vaulting tubes and pitched brick vaulting, it was only long after they had gained acceptance elsewhere in the empire. Even so, the move toward the use of vaulted structures outside of Italy was undoubtedly due in part to the desire of both cities and individuals to express their *Romanitas* – to demonstrate that they belonged to something greater. Architecture was one of the most visible and long-lasting means of making one's mark in the competition for prominence.

When I began this project I did not know exactly what themes would develop out of the material I had collected in the various databases (WebCats. 1–7). As those databases grew and the GIS distribution maps changed, so did my ideas regarding the significance of the techniques and where they were used. Ultimately, three interconnected themes

Catalogs (WebCat.) and color figures (WebFig.) can be downloaded at www.cambridge.org/vaulting

developed: the importance of the spread of bathing culture, the roles of both agricultural production and the pottery industry in creating contexts for innovation, and the intertwining of regional and long-distance networks of various types (economic, cultural, social, and military) in the diffusion of knowledge. Hence, in this final chapter, I explore the areas where two or more of the vaulting techniques come together to share a common theme and in doing so present a broad overview of the web of factors influencing the innovations examined in the preceding chapters.

THE ROLE OF BATH BUILDING IN TECHNOLOGY TRANSFER

An examination of the databases reveals the overwhelming predominance of bath buildings. The bath became the symbol of Roman culture and civilized life, and by the imperial period it was among the first amenities added to new or existing cities within the Roman sphere of influence. Because of its solid construction, it was also one of the building types most likely to leave tangible remains. Nevertheless, its survival rate over time is not an adequate explanation for its ubiquity in the databases – theaters and amphitheaters also survive well in the archaeological record, but they rarely employed new or innovative vaulting techniques. The bath is so dominant because it required the highest degree of available technical expertise to design and build both the water and heating systems and was therefore more likely to require specialists, who were better equipped to make innovative technological advances. Moreover, terracotta elements were critical for the heating systems employed in floors and walls. Clay can be easily modeled into different shapes, thus offering the tile maker creative opportunities. Moreover, it is the ideal medium for low-investment experimentation. Once fired it also has the obvious advantage of being both fireproof and waterproof. An additional advantage is that terracotta has a lower thermal conductivity (0.75 W/mK) than limestone (1.3 W/mK) or sandstone (1.7 W/mK), so it retains heat better. The craftsmen who made the terracotta building elements integrated them into the milieu of building construction in ways that went beyond the longstanding tradition of supplying terracotta roof tiles. Hence both the social connotations and the technological requirements of the bath building made it a nexus of technology transfer in the Roman world.

Two of the techniques examined, vaulting tubes and armchair voussoirs, have roots in the early period of Greek and Roman bath development. The vaulting tubes employed at the North Baths at Morgantina (mid-third century BCE) represent an early attempt to replace the standard wooden roof structure of a bath complex with elements of terracotta. Large curved tubes were used to create both the barrel vaults and the dome covering the circular room containing individual bathtubs, which were typical of Greek baths. Such Hellenistic Greek baths were clearly early laboratories for experimental vaulting. The bath at Taposiris Magna (first half of second century BCE) is a case in point (Chapter 7). Much of the bath was cut into a rock cliff, but one of the rooms projecting from the cliff was covered by a cut stone vault employing joggle joints between the voussoirs.[2] This was a method in which each voussoir has a mortise on one side and a tenon on the other, so that the mortise of the upper voussoir rests on the tenon of the lower one. This device first appears in Hellenistic Egypt. Other examples are known in vaults from the Ptolemaic tombs at Kom Abu Billo (ancient Terenouthis; c. 2 m span).[3] The precocious use of the joggle joint for the vault at Taposiris Magna is also suggestive of the types of innovations that were probably occurring in arches and vaults at Alexandria itself (Chapter 4). The same device was used periodically in Roman architecture, especially for flat arches (e.g., the Baths of Sulis Minerva at Bath and the theater at Orange, WebFig. 32); it was only rarely used for vaults, although it appears in some second-century CE sail vaults from tombs at Ezbet Bashendi, Egypt.[4]

During the second century BCE, we also find the second stage in the development of vaulting tubes (Chapter 5) at the bath at Cabrera de Mar in Spain. These are the earliest known baths from the Iberian peninsula, and they occur in a short-lived settlement (mid- second century–early first century BCE) less than a kilometer from the indigenous *oppidum* of Burriac, which at this time was a center of coastal trade. At the end of the third century, the Romans had taken control of this area during the Second Punic War, and the disappearance of the grain storage buildings that had been a sign of the indigenous elite who controlled the land suggests a corresponding change in land use and power structures. The baths appear in the mid-second century when the area apparently underwent widespread resettlement. On the basis of the advanced technology displayed in the bath, as well as its affinities with early bath plans in Italy, scholars have assumed that the settlement included Italian immigrants living alongside the indigenous people.[5] Even so, it is worth pointing out that, in spite of the Roman type plan, the baths employ some distinctly non-Italic building techniques. As we have already seen, the vaulting tubes only have a precedent in Greek Sicily. Moreover, the walls are built in a local manner with irregular stones bound by clay and then coated with waterproof mortar consisting of a layer of ash mortar topped by a layer of *cocciopesto*. The use of ash mortar is most often found in areas of Punic influence in the western Mediterranean (Chapter 2) and is not found in Italy (Fig. 9D). The same combination of ash mortar with *cocciopesto* was used elsewhere in Spain in the late second-century BCE Republican bath at Valencia and in the mid-first-century CE Bath 1 at Labitolosa.[6] The design of the bath may well have come from Italic prototypes, but the materials and techniques used to build it were of Greek and Punic origins.

Yegül has recently emphasized the complex relationship that existed among Greek, Punic, and Roman type baths during the third through the first centuries BCE and argued that the development of bath buildings along different cultural lines was a result of the complex shift of peoples at this time.[7] The same can be said of the techniques used to build them. The period of the Second Punic War at the end of the third century BCE threw together Greeks, Carthaginians, Iberians, and Romans as domination over the western Mediterranean was negotiated. Just as the mix of cultural habits was transformed into new architectural forms, so too were the methods used to build them. The bath at Cabrera de Mar went out of use by the first century when the settlement was replaced by nearby Iluro around 80–70 BCE. At around the same time, Baetulo was founded about twenty kilometers farther south, and its bath was the one with unusual H-type vaulting ribs (Fig. 105). The craftsmen of this area just north of modern Barcelona seem to have been particularly inventive in creating new ways to roof bath buildings.

With the coming of the Romans in Gallia Narbonensis and Hispania and the urban development promoted by Caesar and Augustus during the first century BCE, the demand for bath buildings increased over the following century when armchair voussoirs began to be used. They filled a need for an easy-to-build and economical vaulting system (Chapter 7). Both vaulting tubes and armchair voussoirs were known in these areas, but over time armchair voussoirs ultimately became the signature technique, whereas vaulting tubes died out and morphed into the vaulting pots for kiln roofs, which were used for several centuries before the nozzle tubes were developed in North Africa. Why did one technique continue and proliferate and the other did not? One significant factor seems to have been the geological context. When the tubes were reintroduced into North Africa in their new nozzled form, they were used with quick-setting gypsum mortar, which eliminated the need for centering altogether. Gypsum is ubiquitous in Tunisia and surely provided a catalyst for the innovation. The armchair voussoir system, in contrast, used the more common lime mortar and was not dependent on gypsum for its success. Another factor was the manufacturing process – the individual units of the armchair voussoir system were better suited to the craft of the tile maker (the potter's wheel being unnecessary), who would have been already producing other types of brick and tiles for baths. Thus the armchair voussoirs were a more obvious choice for the context of these developing provinces in western Europe.

THE BUILDING INDUSTRY, TERRACOTTA PRODUCTION, AND AGRICULTURAL EXPORT

The relationship between the building industry and agricultural production is clearly evident in the supply of materials to construction sites. Lime and bricks (occasionally with farm animal hoof prints impressed), along with the wood and charcoal to fire them, were often part of the villa economy, as were timber, rope, and baskets. However, less evident is how land use affected constructional decisions in more subtle ways. One question that arises from the distribution maps of the vaulting techniques in this study is why some of the vaulting techniques appear in one place and not another. For example, I just suggested why armchair voussoirs were chosen over vaulting tubes in the early imperial Spain and France, but this does not explain why armchair voussoirs were never adopted in Africa Proconsularis or in the Greek East. Similarly, brick vaulting was much more common in the eastern empire, and pitched brick vaulting was very rarely found in the West. One factor may have been the differing modes of land use that occurred in different parts of the empire. In this section, I explore this possibility along with how land use could have affected the decisions of the wealthy landowners who used architecture as a means to express social status.

We tend to think of constructional innovation as being driven by large public structures, which was certainly the case in Rome, but was clearly not always true outside of the imperial center. One of the more surprising results of this study is the large number of small villa baths that appear in the catalogs of both hollow voussoirs and armchair voussoirs (WebCats. 6–7). As Roman conquest spread throughout western Europe during the second and first centuries BCE, new colonies were built and preexisting settlements taken over. Agricultural development, especially for vines and olives, expanded around the cities, and the landowners who profited from the new wealth gradually modified their rural villas (*pars rustica*) into complexes of greater pretension (*pars urbana*), modeled on those in Italy with mosaics, painted walls, and private baths. This move toward the *pars urbana* was apparently a driving force behind the diffusion of hollow voussoirs and armchair voussoirs, the majority of both occurring in villa baths.[8] The distribution of hollow voussoirs is unusual because they are found almost exclusively in Britannia and can be linked to factors quite specific to that island province (Chapter 6). Even though armchair voussoirs had a much broader area of distribution, they never went eastward into the Greek world or even into the eastern areas of North Africa (Chapter 7). Why would this be so?

A major factor affecting the distribution of the armchair voussoirs may be the different method of estate management outside the western European provinces. As we have seen, the armchair voussoirs were commonly used in small villa baths attached to the *pars urbana* of a rural villa. Although the wealthy throughout the empire had their country houses, the type of investment in the *pars urbana* that one sees in the West is not as evident in the Greek East or even in Africa Proconsularis. This could partly be an accident of history because there has been more focus on rural sites in these western areas,[9] but even so, recent research suggests that estate management in the East and in Africa took a different form from that in the West.[10] P. Thonemann has examined patterns of land tenure in western Asia Minor and found that it included very large estates, with absentee landlords overseeing properties (often noncontiguous) that were located side by side with small independent landholders.[11] S. Mitchell's study of Anatolia, farther inland, also found evidence of large estates overseen by imperial freedmen or private individuals.[12] Similarly, the inscriptions from Tunisia near Dougga (Chapter 5) indicate a reliance on sharecroppers (*coloni*), at least on the imperial estates. L. Nevett also pointed out that the numerous mosaics from North Africa that illustrate rural life, in fact, all come from urban dwellings, whereas the most spectacular mosaics from the West tend to come from rural villa sites.[13] If the armchair voussoirs represent an outgrowth of the spread of luxurious villa life among the wealthy landowners in the West, it is no surprise that the technique did not travel to areas where modes of self-representation focused more on urban life. Particularly in the Greek East, there was a long history of urban rivalry before the arrival of the Romans, and the elites were acting within a cultural milieu in which the city was the stage.

Patterns of land tenure may also be a factor in the upsurge of brick vaulting in areas of Greece and Asia Minor during the second century. In Chapter 3, I suggested that the decision to use bricks may have been as much about imitating similar land exploitation strategies used in Rome as about imitating the building methods of the capital. The rich array of brick stamps in Rome provide the names of many of the senatorial landowners in the Tiber valley, and a few can be identified as senators from western Asia Minor – Cuspius Rufinus (Pergamum), Cusinius Messalinus (Ephesus), and Ti. Claudius Celsus Orestianus (Pergamum)[14] – who surely had landholdings in their home territories and may well have started to exploit them in the same manner. By the second century, when brick vaulting became common, various modes of landownership are attested in the Greek East – private individuals, cities, and sanctuaries – each of which could obtain revenue from leasing clay beds to brick makers. Unfortunately for our purposes, the practice of stamping bricks in the East was not as common as in Rome, and those that were stamped have not yet been subject to systematic study. Further examination of the unpublished stamped bricks might one day shed additional light on the situation, but we will probably never have as a clear an understanding of brick production outside Rome simply because production never reached the same "industrial" scale and therefore lacked the organization and consistency that can be detected at the capital.

The nozzle-type vaulting tube was the latest of the terracotta innovations in this study to be introduced, and its appearance in Africa Proconsularis followed the great period of agricultural expansion during the second century CE (Chapter 5). The earliest nozzle tubes might have appeared by the first half of the second century, but they only became common at the end of the century under the Severans, when African olive oil destined for Rome began to replace the Spanish oil from Baetica as the major supplier of the *annona*. D. Kehoe has traced how agricultural laws, preserved in the inscriptions found near Dougga, were instituted to protect the shareholders on imperial properties and to encourage the reclamation of abandoned lands by providing tax remittance for investing in long-term crops, especially olives and vines.[15] The archaeological evidence for the change comes in the increased number of remains of pressing facilities and amphora workshops during the second and third centuries from both coastal and inland sites in Tunisia.[16] With the agricultural expansion came the need for more amphoras for export, resulting in increased terracotta production. As in southern Gaul, the production of fine ware grew alongside amphora production, but typically in different workshops, with the amphora workshops tending to be closer to the coast and fine ware farther inland (Fig. 76). In Tunisia, much of the oil was produced along the inland steppes, and the fine ware producers could then use the road network built to bring the oil to port.[17] During the first century CE the market for terra sigillata fine ware had been dominated by producers first in Italy and then in Gaul, but in the second century African fine ware, African Red Slip (ARS), employing the same type of shiny red gloss, began to take over the market. The vaulting tubes became common only after the increase in production of these other products, probably as a type of tertiary item made by potters skilled on the wheel. The wealth produced by exports of cereal, wine, oil, fish sauce, table ware, and cookware provided the basis for the euergetic building activities of the elite in North African cities during the third century at a time when many other areas of the empire were facing economic hardships. The vaulting tubes were used for a wide range of building types in vaults both large and small and eventually led to the creation of new vault forms unique to North Africa.

The relationship between the production of terracotta vaulting elements and that of other classes of terracotta items generated different catalysts for construction innovations in different parts of the empire. Most came about because of an existing infrastructure for manufacture and transport that had been established for the export of agricultural products. But the *invention* of a new terracotta vaulting element was just the first step; only after the context became ripe for mass adoption was there the *innovation*, as seen so clearly in the case of the vaulting tube. In terms of *social acceptability*, the various types of innovations in vaulting were driven to a large degree by the modes of self-representation adopted by the landowning elite, whether it was via their rural villa, their urban domus, or their euergetic activities in sponsoring public buildings.

DEFORESTATION AS A FACTOR IN CONSTRUCTION INNOVATION?

If agricultural expansion were one factor leading to construction innovation, a corollary to the expansion would be the recession of woodlands. Because three of the techniques examined in this study were aimed at reducing or eliminating wooden centering (pitched brick, vaulting tubes, armchair voussoirs), the possibility of deforestation, how it might be assessed, and its potential effect on the availability and cost of wood is worth examining. Deforestation during the Roman imperial period has long been assumed, but with new methods of investigation available, palynological (pollen) and anthrocological (charcoal) studies targeted on particular regions have allowed for a better understanding of the geographical variations of the phenomenon over time.[18] W. V. Harris has recently provided an overview of the state of research that emphasizes the importance of looking at regional evidence and distinguishing among levels of forest clearance.[19] For the present study, the relevant regions are those where the vaulting techniques were most common, and of those, the ones for which the most useful scientific data exist are in southern France and northwestern Iberia, where the armchair voussoirs were employed. Unfortunately the dating of the pollen evidence for Tunisia, which would be particularly desirable for understanding the spread of vaulting tubes, is not sufficiently precise to establish a clear picture during the Roman imperial period.[20]

Southern France has been a focus of both palynological and anthrocological studies, and indeed French scholars have been at the forefront of applying these analytical methods to archaeological contexts. Pollen studies in the southern Rhone valley have shown clear indications of forest regression and change of species, much of which must relate to the clearance of land for growing vines and olives even before the Roman conquest.[21] One anthrocological study focused on the workshop at Sallèles d'Aude (which produced armchair voussoirs and also employed a mid-first-century CE kiln roofed with vaulting pots). By examining the charcoal remaining in a series of ten kilns that were operating there at different periods between c. 20 CE and the early fourth century, the researchers were able to reconstruct the type of species used for fuel and how they changed over time.[22] In the early history of the workshop much of the fuel came from lowland species (ash, elm), which would have been available near the site, as well as deciduous white oak, which grows at slightly higher elevations. The ash and elm quickly disappeared, and from 40–150/200 CE white oak represented 85 percent of the fuel. During the third century the white oak was gradually replaced by the holm oak (evergreen). Another anthrocological study at the villa of Prés-Bas and the associated workshop at Le Bourbou, about 80 km east of Sallèles d'Aude, found a predominance of holm oak used as fuel throughout the active life of the complex (50–425 CE).[23] The presence of holm oak is often indicative of coppicing because it resprouts quickly once cut, which allows for an efficient replenishment of growth. The predominance of holm oak at both sites (albeit at different periods) suggests that the nearby woodland was managed through coppicing as a means of creating a sustainable fuel resource for firing the kilns. However, once coppiced, the trees no longer produce large timbers suitable for building purposes. In this case, the issue for builders may not have been deforestation in the sense of complete forest clearance, but rather the method of woodland management that was aimed at producing fuel and wood for fencing and trellises, rather than large timbers or boards for construction.

Palynological studies have also been undertaken in northwestern Iberia to assess levels of deforestation. One study of the pollen taken from a peat bog about 30 km north-northwest of Lugo indicates a significant decline in tree pollens during the period 25–340 CE.[24] The authors of the palynological study did not discuss the causes of the reduction during this period, but the most likely factors would be the use of trees for fuel for regional mining activities and possibly clearance for animal husbandry and some vine cultivation (*vitis* pollen was present). Other palynological studies in northwest Portugal and Spain also suggest an expansion of agriculture and a general decrease in arboreal pollen, especially of *pinus*, during the first three centuries of the empire, thus indicating some degree of forest recession.[25] These studies are not as fine-tuned chronologically as those from southern France nor are they focused on the Roman period, but the study samples are useful in that they come from the area of Gallaecia where there were extensive mining activities and in the late antique period a concentration of armchair voussoirs. The changes in the nature of the forest cover may also have been a factor affecting choices made by the builders.

Finally, I argued in Chapter 7 that the armchair voussoir vaults were typically covered with a wooden roof structure, yet I also suggested that a major purpose of the technique was to reduce the amount of wood used in constructing the vaults. Why would the builders care about reducing the centering if they were just going to cover the whole vault with a wooden structure anyway? One answer likely lies in the difference between the two uses of the wooden elements. The roof structure was permanent and was part of what the client was getting for his investment. The centering structure, in contrast, was only used by the builder – it did not remain with the final product; thus it represents one of his "tools." If he could reduce the amount of wood necessary to build the vault, he could offer the client a lower price (or reap a higher profit margin). The incentive to reduce the amount of centering was therefore with the builder, whereas the timber roof structure was a given expectation of the client. In the long run, however, reducing the amount of materials used was to the advantage of both parties.

NETWORKS AND TECHNOLOGY TRANSFER

This study revealed some of the modes of technology transfer throughout the empire, and based on the existing evidence, I speculated on others, including social connections, cultural affinities, trade networks, and military movements. A closer look at these various types of exchange serves to contextualize the results of the individual chapters.

Social networks were undoubtedly an important part of the exchange mechanism, especially for regional distributions, although in the absence of written or inscriptional evidence, they are often difficult to track. I made a first attempt at tracing connections between provincial benefactors in western Asia Minor and the known landowners in the Tiber valley who were producing bricks (Chapter 3).[26] A different type of evidence, bricks exported from Rome, comes from North Africa and provides another glimpse at the connections between brick production and the provincial activities of the senatorial elite. Stamped Tiber Valley bricks from the *figlinae* of Cn. Domitius Tullus, who was proconsul in Africa under Domitian, have been found at Carthage and Leptiminus. His personal connections with this province may account for the early importation of the bricks into Carthage, possibly as ballast on grain ships returning from Rome.[27] Interestingly, in spite of the massive production of other types of terracotta items, bricks were never a typical part of the constructional repertoire in Africa Proconsularis except as specialty materials for bath buildings.

The social connections among villa owners were also a likely means of knowledge exchange related to building construction. Vitruvius states specifically in Book 6, which deals with construction of both town houses and villas, that he is writing to provide information for the educated estate owner (*pater familias*) who undertakes to build his own structures.[28] That he felt obligated to give such advice implies that the patrons were often active participants in the construction process. A useful parallel for the way in which fads could circulate among villa owners is documented for the fishponds of the seaside villas along the west coast of Italy. J. P. Oleson has suggested a role for such private fishpond construction in the early development of hydraulic mortar technology that was used in harbor construction.[29] Seaside villas with fishponds occur in a circumscribed area along the coast of central Italy and were popular from the early first century BCE through the end of the first century CE when more industrial-scale fish farms took over.[30] Varro notes specifically that seawater fishponds were expensive to build, stock, and maintain and were therefore a sign of wealth.[31] Like the villa baths employing armchair voussoirs in France, Iberia, and Britain, they illustrate the competitive nature of neighboring villa owners who were vying for a place within the socioeconomic hierarchy. Unlike the villa baths, however, these elegant fishponds and the competition they engendered are actually documented by ancient authors. Varro even satirizes the owners as expending exorbitant amounts on their fish (pampering them as we do our pets today).[32] As Oleson points out, these villa owners clearly took an active role in adding the ponds to their villas, and no doubt much technical knowledge was exchanged between them, either through written treatises such as those of Varro and Columella or through personal contacts with the experts who built them.[33] A similar phenomenon may be at work in the spread of the armchair voussoir ribbing used in villa baths.

Another means of technology transfer was documented in the discussion of hollow voussoirs (Chapter 6). In Roman Britain, the practice of applying patterns to tiles by means of roller stamps has allowed the tracing of the products of individual workshops and of itinerant tile makers who probably specialized in bath buildings. The workshop that invented the Westhampnett voussoir in Sussex employed a special type of double flue box-tile that worked together with hollow voussoirs to form a modular heating system. With the exception of London, the context for the new tiles was mainly in the baths of private villas in southern Britain. The tiles bore the same group of roller stamps and were all made in the same fabric, which suggests that they were made in a single location and transported to the site. However, the fact that hollow voussoirs had to be formed to fit a vault of a particular span implies that these tile makers were also involved in the design and construction of the bath. Later, during the second century, hollow voussoirs and box-tiles made of different fabrics but bearing the same roller stamp were found in different parts of the province (Fig. 99), thus suggesting that sometimes the tile makers traveled and made their products closer to the building site. The evidence from Britain confirms earlier suspicions that itinerant bath builders existed in the Roman world and that they were one potential agent of the distribution of technological knowledge. The fact that the hollow voussoirs were limited almost exclusively to Britain also points to the regional nature of production modes in the empire.[34]

Trade networks clearly influenced technology transfer in the ancient Mediterranean, and regional networks are revealed most prominently. For example, the identification of Pantelleria for the provenance of pumice in the vaults of the baths at Leptiminus and of Sardinia for the scoria at the Antonine Baths at Carthage emphasizes the regional nature of the trade in building stones in this central zone of Mediterranean commerce (Chapter 2).[35] Both islands were primary providers of millstones for grain and were used as transhipment points on routes between the major ports at Carthage, Portus, Narbo, and Tarraco in the West and Alexandria in the East.[36] These building stones were not driving the trade, but the established routes provided the opportunity to acquire lightweight volcanic stones that were not locally available in Africa Proconsularis, the wealthiest of the North African provinces. A similar type of regional trade for vaulting *caementa* seems to have existed for the volcanic scoria from the Ceyhan-Osmaniye scoria cones in Smooth Cilicia.[37] The early distribution of the armchair voussoirs along the southern coast of France and Spain (at Olbia, Baetulo, and Carteia) also suggests that the intense trade along this route could have been an early means of information exchange.[38] The later diffusion roughly followed the coasts and their connecting rivers, with the Garonne river valley acting as the major connector between the Mediterranean and the North Atlantic. The pattern was in part determined by the prominence of baths in villas, which naturally occurred in agricultural zones often fed by rivers and their tributaries. This is not to say that the armchair voussoirs themselves were shipped long distances but rather that traders, boatmen, and ship captains who plied the rivers and tramped the coasts were potential sources of knowledge transfer.[39] In general, the connectivity engendered by the imperial redistributive mechanisms of the *annona* strengthened the regional networks that made up parts of the whole system.

Diffusion of technical knowledge and manufacturing practices can also be detected in regions that shared cultural affinities (as opposed to direct social connections). Most obvious is the distribution of the tongue and groove wall heating system that often accompanied the use of armchair voussoirs on either side of the Strait of Gibraltar (Chapter 7). Trade across the strait was long established from Punic times, but with the new wall heating system, we see not only objects of trade but also ideas disseminated within an area that had shared a cultural unity long before the arrival of the Romans. Most other wall heating systems, such as box-tiles, *tegulae mammatae*, spacer tubes, and spacer pegs, can be found throughout both the eastern and western parts of the empire, so the tongue and groove system is unusual in being limited to this area of the "Circle of the Strait." Similarly, the fact that hollow voussoirs were used almost exclusively in Britain points to a *cultural acceptance* of the technique that emphasizes the insularity of that province (Chapter 6). Another example of building technology with cultural associations was the use of organic plant ash mortar. This was probably a Phoenician technology that came westward to North Africa with colonization and then later spread to areas of Punic influence in the West, such as Sardinia, Pantelleria, and southern Spain (see Chapter 2).

The military has long been recognized as an important source of technological know-how;[40] however, in this study I found little evidence for the military as the source of the *invention* of the techniques discussed, but it often appears as an agent of transmission. For example, the *diffusion* of vaulting tubes outside of Africa Proconsularis can clearly be connected with the military in Britain because the tubes only appear at the military bases of Caerleon, Chester, York, and Chesters. Likewise, the use of vaulting tubes at Dura-Europus was probably due to the military stationed there. The armchair voussoirs in Britain are associated with military sites at eleven of the sixteen sites (69%) for which a context can be identified (not including London), and two examples bear military brick stamps. Because the majority of uses outside Britain are civilian, one source of technological knowledge could have been through military recruitment from areas of Gaul and Spain where the technique was used.[41] As shown by the story of the retired military engineer in North Africa, Nonius Datus, veterans with special skills were also a source of expertise (Chapter 1). Although the evidence is circumstantial, I suggested that military personnel under Hadrian introduced vertical brick barrel vaulting into Greece at Athens, Eleusis, and Argos. Again, the military cannot be credited with the invention because both pitched and vertical mud brick vaults existed earlier in the Near East, but Roman builders (whoever they were) adapted the technique to solve problems that they encountered in building underground channels for aqueducts and drainage projects, the type of projects in which military builders are known to have participated elsewhere. In fact, the presence of specialists and soldiers traveling with Hadrian in Greece is documented by a set of inscriptions found at Coroneia in Boeotia that describe a drainage scheme for Lake Copaïs.[42] The military may have had a role in the innovation, and it clearly played an important role in the diffusion of some vaulting techniques, but the evidence does not indicate that it played a major role in the invention of any of the techniques.

Lastly, one wonders to what degree written sources could have influenced the transmission of ideas. No direct evidence survives for the genre of subliterary texts that are suspected to have existed,[43] but there is plenty of indirect evidence for the recording of technological advances in writing and images, first in the Hellenistic Greek world and later in Latin texts. That technical drawings must have circulated is implied by numerous examples of scaled drawings recorded on stone and papyrus and in mosaic.[44] The circulation of texts among the educated elite and specialists is confirmed by treatises such as Vitruvius's *de Architectura* and the earlier ones that he drew on, such as the writings of Alexander's military engineer Diades and those of the inventor Ctesibus.[45] We even know that Heron of Alexandria (second half of first century CE) wrote a now lost treatise called *On Vaulting* (*Camarika*).[46] If subliterary forms existed, they have not been preserved, although Egyptian garbage dumps such as Oxyrhynchus may hold ever more treasures waiting to be found.

Alexandria, with its think tank based at the Library, surely played a role in creating the intellectual milieu in which both the practical and theoretical bases for thinking about vault forms and ways of creating them occurred. I suggested in Chapter 4 that the development of the sail vault, which appears in the Fayum, can probably be traced to an Alexandrian interest in geometrical forms. Of the vaulting methods examined, the earliest is the vaulting tube used at the North Baths at Morgantina created under Hiero II, tyrant of Syracuse and relative and friend of Archimedes. I hesitate to make direct connections between the vaulting tubes and Archimedes himself, but as noted by Lucore,[47] his presence in Syracuse and his continued contact with the greatest thinkers of the time with whom he had studied at Alexandria must have had an effect on the creative thinking within Hiero's kingdom during the third century BCE. One aspect of the vaulting tubes at Morgantina and later at Cabrera de Mar was the use of iron connectors, which suggests a rather mechanical approach to the problem of vault stability, perhaps inspired by the inventors like Ctesibus who delighted in inventing new gizmos (water pumps, mechanical clocks, water organs). The tubes at Morgantina reveal a certain amount of experimentation, whereas those at Cabrera de Mar display a well-developed conceptual intricacy, with interior sleeves for iron bars provided in some of the tubes. Thus far no other attempts at tube vaults have been recorded during the century separating these two examples, but the difference between the two applications at Morgantina and Cabrera de Mar suggests further development during the intervening period, and some form of written (or drawn) documentation seems likely. These early examples of the tubes with iron connectors involved a complex assembly process that was later replaced by the simpler nozzle tube. Ultimately the success and large-scale adoption of a vaulting technique relied on its ease of use rather than on its complex or intricate assemblage.

CHRONOLOGICAL PATTERNS

The third and second centuries BCE clearly represent a period of great creativity and experimentation that led to new inventions in construction technology, but the innovations, i.e., the adoption and implementation, only came later and in different times and places. In western Europe and Britain, the Flavian period is when the hollow voussoirs and armchair voussoirs began to proliferate, whereas in the Greek East, especially Asia Minor, the use of various types of brick vaulting came during the second century, especially under Hadrian. In North Africa, the homeland of Septimius Severus, the use of vaulting tubes only became common at the beginning of the third century. In each case, the adoption of the vaulting technique corresponded to a time when the region was on the rise in terms of agricultural production and the growing prominence of its elite, as shown by the origins of the members adlected into the senate at Rome. This pattern is not surprising, but it confirms that the adoption and spread of the vaulting techniques reflected broader trends in society. A more general observation is that the techniques in the West often grew more out of the art of the potter and tile maker than of the builder or architect. In the West, the techniques tended to consist of new forms of building elements (the hollow voussoir, the armchair voussoir, and the vaulting tube), whereas in the East they were more focused on the way standard elements were put into place and on the structural relationship between parts of the building as whole. Unlike the eastern provinces, which had a long and revered history of monumental building in stone, the western provinces were not nearly so urbanized when the Romans arrived. Consequently, they were less bound by strong architectural traditions and were quicker to develop entirely new ways of building vaults to achieve their ends in the most efficient manner.

Hadrian deserves a special place in the discussion of building in the Roman Empire because he is the emperor most known for his passion for the provinces and for his generosity.[48] Dio Cassius notes, "He had seen many of them [cities], – more, in fact, than any other emperor, – and he assisted practically all of them, giving to some a water supply, to others harbors, food, public works, money and various honors, differing for the different cities."[49] Moreover, Aurelius Victor comments that "for in the likeness of military legions, he had ordered into cohorts builders, measurers, architects, and every type of person involved in building or decorating walls."[50] Hadrian, who had been given the nickname "*graeculus*" as a boy, was known as a great Hellenophile, and an examination of his building projects outside of Italy reveals that he was clearly focused on the East. In M. T. Boatwright's list of public building and engineering projects (n = 52), 54 percent were in the East and 37 percent of those in the West were in Italy, leaving only 9 percent in the western provinces. However, even in the East Hadrian was using building projects in a very targeted manner: to boost the infrastructure that supported the economy and the military and to rejuvenate the cultic and religious landscape as a means of promoting prosperity and integrating the Greeks into the Roman Empire.[51] In this study, we have seen the fruits of some of these projects with the introduction of vertical brick vaulting in the aqueduct at Athens and in the drains at Argos and the use of radial brick vaulting at the *horrea* at Patara, which is the earliest securely dated example from Asia Minor (129 CE; Fig. 20).[52] In the realm of religion, we may have an example of Hadrian's largesse in the extraordinary vaulted roof of the cult building at Argos.[53] The Harbor Baths at Ephesus were likely part of Hadrian's larger urban project to restore the harbor (for which he was credited)[54] and to build his *neocoros* temple (Chapter 3). Otherwise there are few projects in this study that can be directly associated with him, but Hadrian's influence over the elite benefactors in Greece and Asia Minor seems to have promoted an increase in building. In contrast, his aid in the West took a different form and affected the narrative of this study in an even more indirect manner, such as through road building and repair and legislation like the *lex Hadriana*, which affected agricultural development in North Africa (Chapter 5).

Like Hadrian, Diocletian was an emperor known as a builder. Lactantius says of him, "To this was added an unbounded passion for building and a corresponding exaction from the provinces in supplying workmen and craftsmen and wagons and everything that is required for building operations. Here a basilica was built, there a circus, here a mint, there an armament factory, here a house for his wife, there one for his daughter."[55] Indeed, we see a shift from the earlier innovative brick vaulting, which occurred in privately funded projects, such as the Terrace Houses at Ephesus or the West Mausoleum at Side, to the imperial tetrarchic palaces at Split, Thessaloniki, and Gamzigrad. Diocletian's reorganization of the provincial administration also led to political and social changes that affected private construction. Accompanying the new social mobility that came with the reorganized provincial governing structure (Chapter 1) was an even greater shift toward expressing status through the decor and amenities of one's extra-urban villa. This is especially visible in the pattern of late antique bath buildings whereby many of the urban baths go out of use while private villa baths were renovated or constructed anew.[56] S. Esmonde Cleary has seen this change as representative of "the displacement of civic functions in the private sphere."[57] Nevertheless, as K. Bowes points out, the urban centers housing the new bureaucratic class, such as Arles or Trier, continued to flourish. This shift in attitude and geographical emphasis is evident in the proliferation of villas during the fourth century in Iberia and Aquitania, many of which had baths employing armchair voussoirs. Upwardly mobile members of the imperial court who were rubbing shoulders with the old aristocracy emulated the traditions of the venerated senatorial class in Rome by expending resources on self-display inherent in this type of villa culture.[58]

The present study ends in the fourth century after Constantine adopted Christianity and then moved the imperial seat from Rome eastward to his new foundation of Constantinople. This change, along with Diocletian's recent reorganization, resulted in radically different dynamics in building construction that are worthy of a separate study. The move magnified the split between East and West, and eventually the united empire as it had existed for five centuries ended when Romulus Augustus, emperor in the West, was deposed by Odacer in 476 CE. The power base at Constantinople continued and eventually became the center of the Byzantine Empire. Two of the terracotta vaulting techniques – vaulting tubes and brick vaulting – continued well after Constantine and reached their apogees under Justinian in the sixth century. The lightweight dome of San Vitale at Ravenna in the West was the ultimate expression of the vaulting tubes, whereas the masterpiece of brick vaulted construction was created in the East at Constantinople with the ethereal central domed space of the Hagia Sophia.

NOTES

CHAPTER 1. INTRODUCTION

1. Greene 2008: 76–80.
2. Renfrew 1978.
3. Schlebeker 1977; White 1984.
4. Greene 1992: 101, Greene 2008: 75.
5. Durm (1905) also included buildings outside Italy, but his work was a survey (often based on Choisy) and did not focus specifically on regional distinctions in building techniques.
6. Adam 1994; Dodge 1987, Dodge 1990; Yegül 1986, Yegül 1992. For a recent survey of ancient construction techniques, see also Bianchini 2010.
7. Finley 1985.
8. Hodges 1970; Landels 1978.
9. Greene 2008: 62–72; A. I. Wilson 2002.
10. DeLaine 1997.
11. Bonetto et al. 2014; Camporeale et al. 2008; Camporeale et al. 2010; Camporeale et al. 2012.
12. Freeman 1996; Hingley 1995.
13. Tac. *Agricola* 21 (Trans. Woolf 1998: 69).
14. Millett 1990: 37–38.
15. Hingley 1996: 39–42.
16. Alcock 2000: 224.
17. On the complexities, see Mattingly 1997.
18. Ward-Perkins's ingrained assumptions are occasionally revealed in dismissive language such as referring to North Africa as a "remote backwaters" that was "never a creative centre in its own right" but was "ready to receive and to put to good use the architectural creations of others" or that "there was nothing comparable in Gaul to the revolution in architectural ideas and building practices that was taking place in Rome itself and in Central Italy" (Ward-Perkins 1970: 4, Ward-Perkins 1981: 396, 412). Such language and preconceptions were typical of this generation of scholars, but they generally reflect broader social attitudes rather than personal prejudices.
19. Fagan 1999: 136.
20. Barresi 2003: 133, table II; Schorndorfer 1997: 18–21, 118–20.
21. Boatwright 1991; Hemelrijk 2004. For women sponsoring baths, see Fagan 1999: 159–60.
22. Reynolds 1990: 38; Rumscheid 1999: 26–28 (Aphrodisias), 32–35 (Euromos).
23. Pliny, *Ep.* 10.39.
24. Dio Chrys. *Or.* 40.7–9.
25. Fagan 1999: 142–54.
26. Woolf 1998: 34–47.
27. Pliny, *Ep.* 10.39.
28. Schorndorfer 1997: 20.
29. *Dig.* 50.10.3 (Trans. Watson 1992).
30. Pliny, *Ep.* 8.24; Jones 1940: 136–37.
31. Pliny, *Ep.* 10.40 (Trans. B. Radice, Loeb 1969).
32. Cities in Roman Asia with "free" status include ones such as Ephesus, Pergamum, Sardis, and Aphrodisias.
33. Philostr., *VS* 2.548 (Trans. W. C. Wright, Loeb 1952).
34. Greene 1992: 103–05.
35. Pliny, *Ep.* 10.41–42.
36. *Dig.* 1.16.7.1
37. In North Africa military involvement in aqueduct building has been documented at Verecunda, Timgad, and Lambaesis (Fentress 1979: 165). Similar examples have been found in other parts of the empire such as at Dalheim in Germany (MacMullen 1959: 218) and at Caesarea in Israel (Boatwright 2000: 118). At the aqueduct (mid-first century CE) supplying Fréjus in France, a relief portrait of a Roman legionary (possibly a centurion) was mounted above one of the arches crossing a valley, which suggests that he was involved in the project in some way (Fevrier 1979; Gébara and Michel 2002: 236–37, figs. 175–76, 263 (on dating)).
38. *CIL* 8.2728 = *ILS* 5795; Horsfall 1981: 5–6; Laporte 1997.
39. Plut. *Moralia* 498F. Translation based on W. C. Hembold (Loeb 1939).

40. Jones 1940: 237–38. For *curator operum* dealing with *contractors*: Dig. 50.10.1–2; 50.10.2.1. For ἐπιμελητής: Mitteis and Wilcken 1912: 1.34 = Grenfell and Hunt 1898: 111–12.
41. Martin 1989: 103–13.
42. Riggsby 2010: 217–22. For Roman Egypt, which had Egyptian, Greek, and Roman law, see Taubenschlag 1955: 1–55, 376–80.
43. Dates proposed for the inscription range from the Trajanic/Hadrianic period to the third century. The name Ulpianus (from Trajan's family name) suggests a date of the Trajanic period or later, but others with the name Ulpianus are known to have held the priesthood of Prophet of the God during the third century. The letterforms suggest a date in the Antonine or Severan period, and the building ornamentation has been dated to the early third century (Herrmann 1998: 122).
44. Herrmann 1998: 122–23. Translation based on Fontenrose 1988: 193–94 and Buckler 1923: 34–36. Buckler interprets the final part of the question as "should they consider employment given by their native city or employment of some other kind?" Both Fontenrose and Robert (1968: 581 n. 4) have doubts about this interpretation, although Parke (1985: 76–77) accepts it in his translation. I opted for Fontenrose's more minimalist interpretation.
45. Herrmann 1998: 122–23; Fontenrose 1988: 193–94; Parke 1985: 76–77; Buckler 1923: 34–36; Hellmann 1999: 111–12.
46. Heather 1998.
47. Bowes 2010: 90–93.
48. Ochsendorf (2006) gives the minimum arch thickness (t) to radius (R) ratio (t/R) as 10.75%, where t is the arch thickness and R is the distance from the center of the span to the *centerline* of the arch thickness (as opposed to the intrados of the arch (Rintrados)). Rather than expressing the ratio as a fraction using R, I converted the principle to a proportional ratio of the arch thickness (t) to the arch-free span (diameter (D)), because this ratio is conceptually more meaningful for architects and archaeologists dealing with on-site dimensions. The formula for making this conversion from R to D is the following: $D = 2R - t$.
49. For building domes without centering in West Africa, see www.dwf.org/en/content/dome (last accessed June 27, 2015). There are also numerous videos on the Internet showing people building small radially laid brick domes (often for pizza ovens) using no centering.
50. Heyman 1995: 41.
51. Zessin et al. 2010: 139–41. They give minimum t/R (thickness/radius) = 0.04, where t = dome thickness and R = distance from the centerline of the span to the *centerline* of the dome thickness. This translates to t/D = 0.0204, giving a ratio of dome thickness to free span (t:D) of 1:49 (see note 48 for further explanation).
52. Choisy 1873: 92, Choisy 1899: 523. For further discussion, see Lancaster 2009a: 308–10.
53. Blake 1959: 163; Ward-Perkins 1958: 80, Ward-Perkins 1981: 101; Adam 1994: 177.
54. Bazant and Wittmann 1982; Nilson and Darwin 1997: 33–52. For a brief, less technical explanation, see Lancaster 2005a: 53.
55. Lancaster 2005a: 158–61.
56. Lancaster 2005a: 22–50.
57. Nohlen 2009.
58. I know of some examples of vertical tubes that do not appear to be drains: the vaults at Trajan's Markets, the Basilica of Maxentius (Amici 2005: 136–44), the Severan Baths on the Palatine (shown on plan in Lancaster 2005a: fig. 85), the Small Baths at Hadrian's Villa, West Baths at Cos, and the Leonidaion Baths at Olympia (WebFig. 20).
59. Steskal and La Torre 2008: 40–41, 50–51, Taf. 228.
60. MacDonald 1982: 41–46; Ward-Perkins 1981: 97–120.

CHAPTER 2. *OPUS CAEMENTICIUM*

1. Eckel 1907: 96, 118–22.
2. Lancaster 2005a: 53–54.
3. Wiss et al. 1930; Eckel 1907: 14–15, 31–32. Strength: Merriman 1920: 433. Alberti 2.11 says lime needs about sixty hours of burning as opposed to twenty hours for gypsum.
4. Ward-Perkins 1981: 98; Yegül 1986: 123 n. 15.
5. Oleson provides an excellent compendium and commentary on all ancient passages related to Roman concrete technology in Brandon et al. 2014: 11–36.
6. Vitr., *De arch.* 2.4–6.
7. Philippi: *CIL* 3.633; see also J. P. Oleson's comments in Brandon et al. 2014: 11. Lavernae: *CIL* 1. 1793.
8. Ward-Perkins 1981: 275–76.
9. MacDonald 1958: 7 n. 4.
10. Plin., *HN* 16.202, 35.167; Brandon et al. 2014: 18, 26–28.
11. Vitr., *De arch.* 2.6.1.
12. Plin., *HN* 16.202, 35.166–67; Brandon et al. 2014: 18, 26–28.
13. Strabo 5.4.6; Brandon et al. 2014: 24.
14. Vitr., *De arch.* 2.4.5.
15. Plin., *HN* 36.175.
16. Vitr., *De arch.* 2.4.2–3, 2.6.1–6. There has been much discussion regarding the meaning of *carbunculus*, but most scholars agree that it must be some form of unconsolidated or semi-consolidated ash found throughout the volcanic districts north of Rome. For further discussion, see Oleson in Brandon et al. 2014: 19.
17. Jackson et al. 2007: 30 n. 9.
18. Massazza 1998: 473–78.
19. Theophr., *On Stones* 19. Cos: Livadiotti 2006: 183. Melos: Shelford 1982: 78–81.
20. The term *pozzolan* has come to have a broad meaning among engineers and material scientists so that it now refers to any natural or artificial substance that contains soluble

silica (and often alumina) that can chemically combine with lime to create hydraulic mortar.

21. Vitr., *De arch*. 2.4.1; see also Jackson et al. 2007: 38–39.
22. Cf., Jackson interprets this description as a method for distinguishing between Pozzolane Rosse and Pozzolanelle (Jackson et al. 2006: 1698–1700).
23. Massazza 2002: 328.
24. Jackson et al. 2009: 2484; Jackson et al. 2010: 39–40.
25. Lechtman and Hobbs 1986: 96–97; Jackson et al. 2013; Jackson et al. 2014: 18487.
26. Massazza 1998: 487, Massazza 2002: 330.
27. He et al. 1995: 1696; Chakchouk et al. 2006; Baronio and Binda 1997.
28. Frizot 1975: 316. For firing temperatures see Cuomo di Caprio 2007: 27; Cairo et al. 1997: 167–68.
29. Peña 2007: 263; Davis and Humphrey 1981: 45.
30. Coutelas 2009: 20–21 recommends particles less than 75 μm in diameter.
31. Cuomo di Caprio 2007: 63; Picon 1998.
32. Cuomo di Caprio 2007: 139. For kaolonitic deposits on Melos: Shelford 1982: 80–81. For kaolonitic sand in the mortar of baths of Vieil-Evreux, France: Coutelas et al. 2004: 130.
33. Chakchouk et al. 2006.
34. Tsartsidou et al. 2007: 1272–74; Rogers 1991: 26; Biricik et al. 1999; Dunn and Rapp 2004: 154.
35. Lancaster 2012a; Şahin et al. 2006.
36. Biricik et al. 1999; Şahin et al. 2006; Bellizia et al. 2002.
37. Toprak 2007.
38. Vitr., *De arch*. 2.4.2.
39. Brandon et al. 2014: 153–59, 185.
40. Callebaut et al. 2000; Degryse et al. 2002.
41. Side: Lamprecht 1984: 62–63. Pergamum: Özkayaa and Böke 2009.
42. Brinker and Garbrecht 2007: 100; Garbrecht 2001: 25.
43. Lamprecht 1984: 46–49.
44. Massazza 1998: 476–78.
45. Frizot 1975: 281–82 citing Znatcho-Jaworski.
46. Davis and Humphrey 1981: 45; Gerdes et al. 2012.
47. Cara et al. 2007: 255–56.
48. Brandon et al. 2005, Brandon et al. 2014; Gotti et al. 2008.
49. Vitr., *De arch*. 5.2.1.
50. C. F. Giuliani has shown that the term *opus signinum* probably did not refer to mortar with crushed terracotta in ancient literature, but rather to a building method (Giuliani 1990: 171–74, Giuliani 1992: 89–94).
51. Autun and Escolives: Frizot 1975: 215, 287–88, 313. Thermes d'Esplanade at Arles: Coutelas et al. 2004: 132–33. Charente and Vienne: Rassineux and Meunier 1989.
52. Cyzicus amphitheater: personal observation. Hasluck and Henderson (1904: 139) report pink mortar in the vaults of the substructure of the Temple Hadrian, but I could not find the pink mortar on my visit to the temple in June 2007.
53. Vagalinski 2002: 279–80; Hoddinott 1975: 154, 166.
54. Oleson 2010: 339, 354.
55. Hagia Sophia: Mainstone 1988: 70; Mark and Çakmak 1994; Moropoulou et al. 2002; Ousterhout 1999: 134. Ravenna: Baronio et al. 1997.
56. Pavía and Caro 2008: 1810. The authors also refer to other examples of ancient mortar containing "organic fuel" surrounded by reaction rims, which imply that C-H-S gels have begun to form in the border zone, but whether this occurs with ash or charcoal particles is unclear, which adds further confusion.
57. The benefit of charcoal as a fuel is that it produces very high temperatures as are necessary for iron smelting (1,150° C), but such high temperatures are not necessary for lime production, which require only those in the range of 900° C. In fact, Cato (*de Ag*. 16, 38) makes clear that firewood (*lignum*) should be used for limekilns or else made into charcoal (*carbo*) only if one cannot sell it.
58. Smith 1998: 197. In Egypt dried manure was a traded commodity from the pharaonic period into the second century CE, when it was sold as a market item around the Temple of Serapis at Oxyrhynchus (Bowman 1986: 107).
59. Theophrastus, *On Stones* 69. The word indicating the cow manure (βόλιτον) on the existing manuscripts is not preserved, but Pliny the Elder (*HN* 36.182) took his account of calcining stones directly from Theophrastus and supplies the missing words (in Latin) as *fimo bubulo*. Theophrastus notes the use of the cow manure in his discussion of calcining γύψος (*gypsos*); however, Caley and Richards (1956: 220–22) argue that his use of *gypsos* is broader than the modern use of gypsum and should be extended to include lime.
60. Most analyses of organic ash mortars have focused on linings of water-containment structures rather than structural uses. One recent study includes both types (Oleson 2010: 354). A 1989 study of the effects of wood ash on mortar concluded that the addition of charcoal and inert wood ash increased the water retention of the lime mortar, which reduced cracking and increased flexural strength. However, the mortar mixes for the analysis used only the nonsiliceous ash from burnt hardwoods, because the ingredients in burnt dung are difficult to control (Goodman 1989: 22–29 [Caesarea mortars], 39 [source of ash from experiments], 129–34 [results of experimental mortars]). Thus the possibility of pozzolanic reactions occurring in the test mortars was eliminated. Studies examining how charcoal and reactive ash might interact to affect the performance of the mortar are still needed.
61. Ford and Miller 1978.
62. Bagust et al. 2011: 459; Mattingly et al. 2011: 215; Smith 1998.
63. Tsartsidou et al. 2007: 1268.
64. Bagust et al. 2011: 454–62. The composition of the structural mortar contained more sand than that of the linings.
65. Kolataj 1992: 85, 176.
66. Adam 1994: 73; Frizot 1975.

67. Bagust et al. 2011: 459.
68. O'Neil and Davey 1945: 103–09.
69. These findings are from a 2004 report: Sabbioni, C., A. Bonazza, A. Sardella, G. Zappia, J. D. Rodrigues, A. M. Esteves, A. S. Silva, J. Cardoso, A. M. Monteiro, L. Marino, R. Sabelli, P. Rendini, T. Akili, M. Doughman, T. Akasheh and M. Shaer 2004. *Sampling of Building Materials from Archaeological Sites in the Mediterranean Basin. PRODOMEA Report*, originally posted on the PRODOMEA website and available at http://digidownload.libero.it/restauroarcheologico/doc/prodomea_Sampling%20of%20building%20materials.pdf (last accessed June 25, 2015).
70. Brandon et al. 2014.
71. Amici 1991: 52, 162; Jackson et al. 2010 (pub. 2011).
72. Lancaster 2005a: 59–64.
73. Lancaster et al. 2011; Lancaster 2011.
74. Taormina Theater and Catania Odeum: Belvedere 1988: 365 n. 129, tav. 6–7, 367 n. 144, tav. 11, 13; Syracuse "Gymnasium": Cavallari and Holm 1883: 399. The scoria has not been analyzed to my knowledge to verify its provenance.
75. Ward-Perkins 1958: 343–46. Bosra: Butler 1914: 260–64. Philippopolis: Butler 1903: 384–90.
76. Lancaster et al. 2011; Lancaster 2011.
77. Lancaster et al. 2010; Spanu 2003b: 25; Verzone 1957: 57.
78. Lézine 1969: 30.
79. Lézine 1969: 30 n. 4.
80. Williams-Thorpe 1988: 284–88; Williams-Thorpe and Thorpe 1989.
81. *Pilae* at Antonine Baths Carthage: Delattre 1908: 592.
82. Arnaud 2005: 24–25, 175.
83. McCann and Oleson 2004: 202–10.
84. Plin., *HN* 36.154.
85. Arnaud 2005: 163.
86. Tunisia: Williams-Thorpe 1988: 296–305. Libya: Antonelli et al. 2005: 140–42.
87. Mosca 1998: 1147–48.
88. Gerdes et al. 2012: 247.
89. Pentecost 1981: 369. Tufa is made up of calcite, which has a specific gravity of 2.7, so a porosity of 50% gives a specific gravity of 1.35 and a weight of 1,350 kg/m^3.
90. Stone 1929: 142 n. 1.
91. Werner 1981: 15–16. I am also indebted to Goran Nikšić, architect in charge of Old Town Split, for sharing his knowledge of the palace and its construction during my visit there in May 2012.
92. Magallón et al. 1995: 173.
93. Krencker et al. 1929: 73–74, Abb. 87a–b. The vault is in room 5 on Abb. 86.
94. Thouria: Vitti 2011: 312–17, Vitti 2013: 178, 184. Corinth: Vitti 2013: 123–24, 130, 202 n. 159.
95. Livadiotti 2006: 183, n. 29; Morricone 1965–66: 7. For testing of the reactivity of the volcanic ash from the nearby Datça peninsula around Cnidos, see Akgül and Tanaçan 2011.
96. Ward-Perkins 1958: 343–46, Ward-Perkins 1981: 275; Dodge 1984: pls. 102, 166, 167. Bosra: Butler 1914: 261–64 notes that one square room (10.8 m span) of the building is covered by a completely preserved cloister vault, but he does not specify how the *caementa* are laid in the mortar. Cf. Spanu (2003b: 25 n. 103) observes that the mortar in the walls of structures with vaults containing volcanic scoria at Tarsus, Anazarbus, and Hierapolis Castabala "does not seem to include volcanic sand." Ultimately, scientific analysis of these structures is necessary to determine the pattern of use of hydraulic mortar.
97. Crete: Maravelaki-Kalaitzaki et al. 2003. Tiryns: Chiotis et al. 2001; Regev et al. 2010: 3001.
98. Vassal 2006: 104–05.
99. Malinowski 1979; Koui and Ftikos 1998.
100. Vitr., *De arch.* 2.4.2, 2.5.1.
101. Coarelli 1977.
102. Livy 41.27.8.
103. Cozza and Tucci 2006. They argue that the structure should be a ship shed (*navalia*), which I find convincing. However, there is still much debate (Arata and Felici 2011). Nevertheless, the argument has served to break the definitive link that has existed between the vaulted structure in Testaccio and Livy's "*porticus Aemilia*" of 174 BCE.
104. Mogetta 2013, Mogetta 2015. At the recent conference "Arqueología de la construcción 5" in Oxford (April 2015), Jacopo Bonetto noted examples of mortar with volcanic ash found at the city walls of Aquileia and Ravenna, which could date as early as the late third century; thus further study is warranted.
105. Given the ambiguity of the identification of the vaulted structure in Testaccio ("*Porticus Aemilia*"), the earliest securely datable vaults in Rome are those of the *via tecta* of the Temple of Magna Mater on the Palatine (111–101 BCE): D'Alessio 2009: 234–36; Mogetta 2013: 127, Mogetta 2015.
106. Brandon et al. 2014: 153–59, 185.

CHAPTER 3. BARREL VAULTS OF BRICK

1. At Ephesus (Harbor Baths, Theater Baths, and East Baths) and Tralles (Uç Goz Baths), the fill above the brick shell also consists of mortared bricks. These are the only examples I have found for which the fill was not mortared rubble; they perhaps represent a Meander Valley peculiarity.
2. Giuliani 2004: 43, figs. 25-29; Lancaster 2005a: 88, fig. 64.
3. Lancaster 2005a: 86–98, Lancaster 2005b: 77–80.
4. Vitti 2014: 254. I thank Paolo Vitti for showing me this during our visit there (June 2013).
5. Orsi 1909: 314–18.
6. Pasqui 1889: 234; Costamagna 2013: 63–64. One tomb found in 2011 is described as having vertical or pitched brick, but illustrations and a detailed study have not yet been published.

7. Ortalli 1987: 166, Taf. 23a.
8. Forlati Tamaro 1965.
9. Cuomo di Caprio 2007: 524, fig. 169.
10. Van Beek 1987.
11. Winter 1993: 12, Winter 2009: 581–82.
12. Malacrino 2007. For bricks (stamped) in fortification walls: Zachos 2007: 278–81.
13. Thanks to Phil Stinson for information on the basilica at Aphrodisias. Thür (2009: 490–92) has found sporadic occurrences of brick in Terrace House 2 at Ephesus that date to the first century CE. For *opus vittatum*: Lugli 1957: 47–48, 633; Adam 1994: 135–39.
14. P. Vitti 2010: 302; Vitti (2013: 165–66, figs. 3.196–99) provides details of the vault remains, noting that it employs bricks about 7 cm thick.
15. Petropoulos (2007: 193–94) dates the tomb to the early first century CE based on the use of a modified version of *opus reticulatum* (with bricks inserted between the reticulate tesserae so as to form a network), the style of the two female portrait heads found within the tomb, the letterforms of the inscription, and the pottery found in the excavation; however, the details of these criteria are not given. The mausoleum was destroyed by a flood in the early second century CE, thus providing a *terminus ante quem*. Based on the tomb form (resembling those at Ostia) and the use of Latin in the inscription, he proposes that the family must be the descendants of one of the original Roman veteran families settled in the new colony.
16. Sinn 2000: 120. The excavators proposed in the 1990s that the structure be interpreted as an athletic guild house, but further work has revealed extensive heating systems that correspond with a typical bath (Haseley 2012). For the dating, see Sinn et al. 1995: 174–75; Martin 2001.
17. Domitianic dating: Petropoulos 2009: 70. Hadrianic dating: Papapostolou 1989: 355–59.
18. Myra: *CIL* 3.232. Patara: *CIL* 3.12129. The Patara inscription is not fully preserved, but the remains of it are identical to the fully preserved one at Myra, which dates to 129 CE.
19. The brick vaulting at the Baths of Vespasian at Patara clearly belongs to a second phase, which is confirmed by the building joint indicating that the westernmost room was added to the original first-century building. The precise date of this addition in unknown, though Farrington and Coulton (1990: 61–62) suggest some time after the earthquake of 141 CE. The Humeitepe Baths at Miletus have been assigned a range of dates from the mid-first century to the mid-second century. The only publication dealing with the evidence for dating is that of A. von Gerkan and F. Krischen (1928). They opt for a date around "the turn of the first to the second century when large-scale Roman building activity starts and Miletus begins to lose its Hellenistic character," noting that there are no inscriptions and very few decorated architectural fragments, so any dating has to be based on the urban context and the building techniques (Gerkan and Krischen 1928: 141). In a recent publication (Blum 2009: 47, fig. 3), the baths are considered to belong to the first half of the second century. Given the paucity of other pre-Hadrianic examples of brick vaulting, a later date seems likely.
20. Domitianic: Alzinger in *RE* supp. 12: 1610–11, s.v. "Ephesos B: Archaeologischer Teil"; Friesen 1993: 122. Hadrianic: Strocka 1988: 302; Scherrer 1995: 12–13, Scherrer 1997b: 118 n. 66, Scherrer 1997a: 112; Quatember 2011: 67.
21. Friesen 1993: 122; *IvE* 2.427; *IvE* 2.508.
22. Quatember 2011: 67, n. 192.
23. Strocka 1988: 302.
24. Scherrer 1995: 13; *IvE* 2.430 (revetment for stoas).
25. Heberdey 1904: Bei. 43.
26. Zabehlicky 1995: 211.
27. Keil 1933: Bei. 17. Other evidence for work on the harbor during the Trajanic period comes from inscriptions noting that T. Flavius Montanus gave 75,000 denarii for work on the harbor some time between 102 and 114 CE and that C. Licinius Maximus Julianus gave 2,500 denarii around 105 CE: *IvE* 6.2061 (Montanus), 7.3066 (Julianus).
28. *IvE* 2.274 (Hadrian and harbor). On the temple, see Karweise 1995: 311–19; Burrell 2004: 67–68; Scherrer 1995: 12–13, Scherrer 1997b: 118 n. 66, Scherrer 1997a: 112.
29. *IvE* 4.1104 1.3–6; 4.1125 1.3–5; 4.1155 1.3–8. (βαλανείον τωο Σεβαστων (*balaneion tou Sebaston*) or βαλανείον Σεβαστου (*balaneion Sebastou*). The inscriptions had been associated with the Baths of Vedius, but they all refer to a *xystos*, which should be the structure that Verulanus and his wife revetted. Friesen (1993: 134–37) argues that the findspots of the inscriptions near the Harbor Baths make them the more likely candidate, though he sees them as referring to baths built by Domitian. However, all of the inscriptions date to the Hadrianic period or later and therefore do not provide evidence for a Domitianic date.
30. Lancaster 2005a: 88–103. See also recent observations for other structural uses of brick vaulting in Rome (Vitti and Vitti in press).
31. DeLaine 1997: 164.
32. Steskal and La Torre 2008: 29, 47, Taf. 147.2–3, 148.1, 198.2, 200.1–2, 202.4, 264.1.
33. Ziegenaus 1981: 46, Taf. 19c.
34. Gerkan and Krischen 1928: 85, Taf. 107–09.
35. Vitti 2011: 305–07.
36. The cross-section of the beams is documented in a medieval manuscript listing the size of the replacement timbers used in the ninth century (Adam 1994: 212).
37. Pliny, *HN* 16:202.
38. Nohlen 2009: 422–26.
39. The holes at the "Baths of Nero" were filled with clay (Vitti 2013: 215 fig. 4.11).
40. Ritti et al. 2007: 139–43, especially 141 for the difficulty of the translation.
41. Ward-Perkins 1958: 93. Tebtunis: Hadji-Minaglou 2007.
42. Husselman 1979: 56.

43. El-Naggar 1999: 145–46, 363, fig. 172.
44. Oates 1970: 22; El-Naggar 1999: 155–57, figs. 182–86; Goyon et al. 2004: 125–30.
45. Vitti 2013: 216.
46. Choisy (1904: 46–48) proposed that the elongated arched forms were laid out using arcs of two different radii. A drawing on an *ostrakon* from the pyramid complex of Djoser at Saqqara (Third Dynasty) shows an arch with a series of vertical measuring lines spaced at regular intervals (El-Naggar 1999: 331–34, 407–10; Goyon et al. 2004: 79), which has been taken to imply that the form was not laid out using radial arcs; however, the vertical lines may simply be interpreted as measuring lines for transferring the form to the centering as opposed to being used to lay out the original form. I thank P. Vitti for pointing out this distinction in the potential purpose.
47. Reuther 1938b: 499.
48. El-Naggar 1999: 255–56, fig. 315.
49. El-Naggar 1999: 152, figs. 178–79.
50. Hooke 1679.
51. Heyman 1988: 739, Heyman 1995: 7.
52. Besenval 1984: 146–47, pl. 202.
53. One notable example is the dome of the "Temple of Diana" at Baiae, which takes an ogival form. For the structural implications, see Cooke and Ochsendorf 2011.
54. Choisy (1883: 35, fig. 34) shows a type of vault where the bricks appear vertical from below, but are actually set tilted back to form what he calls a truncated cone (*tronc de cône*). The Roman ones, however, are not laid in this manner, as is demonstrated by the examples in situ and by the impressions in the mortar where they have been removed. It is unclear whether he ever actually observed this configuration or if it represents an ideal that he conceived on a theoretical basis.
55. *CIL* 3.549 = *ILS* 337.
56. Ziller 1877: 122, Taf. 6, 8.6; Leigh 1998: 71–72. Ziller does not give dimensions for these vertical shafts.
57. Thompson 1960: 348; Walker 1979: 164–66; Leigh 1998: 192–94, Leigh 2000: 118–19.
58. Shear 1973: 159–60, pl. 32b.
59. Lancaster 2010: 449–50.
60. Mylonas 1961: 183–84; Ziro 1991: 217; Clinton 2005: 366 cat. 449. Clinton (2008: 349 cat. 449) reconstructs a partially preserved inscription (*IG* II^2 3196) as the dedication of the aqueduct by Hadrian, but the critical pieces of the text denoting the name of the emperor and the object of the dedication are missing.
61. Paus. 1.38.6. For a more detailed discussion of the dating evidence, see Lancaster 2010: 450–54. For the Temple of Artemis and the fountain phasing, see Willers 1996: 183; Palinkas 2008: 225–28.
62. Vollgraff 1944: 397–400, Vollgraff 1958: 550–55.
63. For a Hadrianic dating, see Banaka-Dimaki et al. 1998: 328 (Greek), 334 (French). More recently M. Piérart (2006) was noncommittal on the date of this aqueduct.
64. Daux 1969: 967–68; Abadie-Reynal 2007: 302–03.
65. Serapeum: Aupert and Ginouvès 1989. Baths: Aupert 1994. Inscription: Aupert 1974.
66. Lancaster 2010: 467–70. The following is a brief overview of the argument for a Hadrianic date. The south aqueduct (C1), which touches walls of both the cult complex and the theater foundations, has been dated by Greek scholars to the Hadrianic period (Banaka-Dimaki et al. 1998: 328, 334). It runs along the east wall of the south parodos, which in turn is contemporary with room A1 of the cult complex. In 1956, G. Roux (1957: 638) noted that the aqueduct channel was contemporary with the south parodos retaining wall, against which the cult complex was built. Aupert (1989: 717) initially agreed, but later changed his mind (Aupert 1992: 362). However, because the two walls share foundations they must represent two phases of the same project. Moreover, because the wall of the aqueduct channel is built against the south parados retaining wall, the cult complex and the aqueduct should all be part of that same project, the date of which depends on the excavated pottery. The date of c. 100 CE was proposed based on the fact that the majority of the pottery dates to the first century CE. However, there are significant examples that are later. Twenty-one percent (n = 30) of the forms could date as late as the mid-second century, and of these, ten date no earlier than the second century. Twelve of the forms were also found in the Hadrianic drain in the agora. Hence, even though a majority of the ceramics clearly dates to the first century, 7% *must* belong to the first half of the second century, and another 7% *could* date to the first half of the second century. Moreover, a majority of this 14% total has been found in Hadrianic contexts in Argos or elsewhere in Greece. More significantly, there are three cases where forms that do not appear before the Hadrianic period are found in the phase 1 trenches. Further evidence comes from the relationship between the south aqueduct and the adjacent theater, but I refer the reader to the appendix in my 2010 article for details.
67. For an in-depth description of the constructional details, see Vitti 2008 (pub. 2010).
68. Lancaster 2010: 454. Loutsa bath: Personal communication from Michalis Kappas. Olympia: P. Vitti 2010: 311, fig. 14. Dion: Karadedos 1990: 219–22, fig. 5; M. Vitti 2010: 334.
69. Crete: Livadiotti 2000. Three-brick vaulted channel at Gortyn: Pagano 1992: 279, fig. 3; Giorgi 2010: 428, fig. 9. An example of a barrel vault with pitched fired brick occurs in a second-century vault (unusual for such an early date) of the Northeast Baths at Epidaurus (Vitti 2013: 113–14).
70. Steskal and La Torre 2008: 29, 47, Taf. 147. 2–3, 148.1, 198.2, 200.1–2, 202.4, 264.1.
71. Thür 2002: 61; Zimmerman and Ladstätter 2011: 48, 54, 78; Thür and Rathmayr 2014: 88.
72. For the second-century dating of the vaults at the Baths of Vespasian, Farrington and Coulton (1990: 61–62) suggest

after the earthquake of 141 CE. For Samos: Martini 1984: 185–86, figs. 66a-b.

73. Lancaster 2009b: 380–81; Ward-Perkins 1958: 96; Waelkens 1987: 99; Dodge 1987: 114.
74. Anamurium: Lancaster 2009b: 382, fig. 16.
75. Giuliani 2008.
76. Choisy 1883: 36.
77. "Baths of Nero" at Olympia: P. Vitti 2010: 310–11, fig. 14; Elaeussa Sebaste: Lancaster 2009b: 381–82, fig. 15.
78. Mark and Çakmak 1994: 277–79.
79. Choisy 1883: 41.
80. For a discussion of the mechanics of the lintel arch, see DeLaine 1990: 410–17.
81. For further discussion of the Izmir basilica vaults, see Lancaster 2009b: 378–80.
82. Lang-Auinger 1996: Taf. 144.
83. I thank Brianna Bricker of the Sardis excavation team for sharing this finding with me.
84. Vitti 2013: 192, fig. 3.251.
85. Bairrão Oleiro and de Alarcão 1973: 356.
86. Lancaster 2009b: 382–83, fig. 17.
87. For the Rotunda, see Ward-Perkins 1958: 89–90, pl. 33A–B.
88. I thank Ursula Quatember for bringing this to my attention.
89. Ward-Perkins 1981: 251.
90. Aupert 1985: 169.
91. Examples of vertically set mud bricks have been found in Egypt at Giza (2465–2160 BCE), north of Aswan at El-Koubania South in Tomb 28.q.2 (2134–1785 BCE), and in Thebes at El-Assasif Tomb TT 197 (26th Dynasty, 664–525 BCE): El-Naggar 1999: 193–94, 234–35, 278.
92. Andrae and Lenzen 1933: 27, 43–44, Taf. 10. For discussion on the disagreement over the date and reconstruction, see Arce 2003: 227–29.
93. Lancaster 2010: 461–63, fig. 28. Reuther (1938a: 423–24, fig. 100) shows the bricks of the vaults as laid vertically, but Lenzen (1955: 122–23) describes the vaults in the palace generally as consisting of bricks pitched against the back wall and gradually becoming vertical through changes in the mortar joints, but whether this also applies to the vaults for the pillared hall is unclear.
94. Tepe Nush-i-Jan: Roaf and Stronach 1973: 137–38, pls. 4–5; Huff 1990: 145–47, Abb. 3; Besenval 1984: 121–23, pl. 154. Persepolis: Besenval 1984: 126, pl. 67b.
95. Van Beek 1983: 17, Van Beek 1987: fig. on p. 83.
96. Hansman and Stronach 1970: 43, fig. 7; Huff 1990: 151, Abb. 8.
97. The standing structure consists of at least two phases, with suggested dates for the first one ranging from the first (Parthian) to the third century (Sassanian) CE, but the consensus is now weighted toward a Sassanian date for both phases: Huff 1990: 152–55); Ghanimati 2000: 144–45.
98. Seleucia-on-the-Tigris: Hopkins 1972: 35, 68, 78, fig. 26. (plan); Yeivan 1933: fig. 9 (plan/section), pl. 20; Nippur: Hilprecht 1903: plate opposite p. 511.
99. Qal'eh Zohak: Kleiss 1973; Pohanka 1983; Besenval 1984: 162, pls. 85b, 85c, 86a; von Gall 1998: Taf. 1.
100. Oates and Oates 1959: 215. Whether these were fired bricks or mud bricks was not made clear, though other bricks on the site were specified as mud bricks.
101. Ward-Perkins 1958: 93.
102. Wulf-Rheidt 2009: 503–04.
103. For the career of Celsus, see Halfmann 1979: 111–12.
104. Strocka 1988: 295, 302–03, Strocka 2003: 39.
105. Waelkens 1987: 96.
106. Steinby 1974–75: 110–11; Plin. *Ep.* 7.19; Bloch 1947: 338.
107. Setälä (1977: 89–91) identifies him as *consul suffectus* in 159 CE. Ti. Claudius Julianus has been also been identified with the *consul suffectus* of 129/130 and the proconsul of Asia in 145 (Halfmann 1979: 147–48). Stamp: Coste 1971: 96, no. 4.
108. Cusinius Messalinus from Ephesus: Setälä 1977: 104–05; *CIL* 15.957–58, S. 280 (123/4 CE). His daughter Cusinia Gratilla: *CIL* 15.959–61 (late 120s CE). Ti. Claudius Celsus may be identified with Ti. Claudius Celsus Orestianus from Pergamum: Setälä 1977: 89–90; *CIL* 15.3.92–95 (123/124 CE).
109. Setälä 1977: 106; Halfmann 1979: 154; *CIL* 15.2322 (153 CE).
110. Halfmann 1979: 148.
111. Habicht (1969: 9–11) argued for a Hadrianic date for its completion, whereas Strocka and Wörrle (2012: 257–59) have recently argued for a later completion date under Antoninus Pius.
112. Corsten 2005.
113. Medri 2001.
114. Broughton 1938: 637–84.
115. Thür 2009: 485, Abb. 1. Other published stamps from Ephesus: *IvE* 2 pp. 237–38, no. 1–7.
116. Dignas 2005: 211–14. For other bricks with stamps referring to deities, see Manacorda 2000: 133, 139; Vecchio 2009–12: 71 n. 93.
117. The relationship of brick maker to landowner could take a variety of forms. For an overview of the subject, see Aubert 1994: 201–321, esp. 217–44.
118. Loots et al. 2000: 687, 693.
119. Broneer 1932: 136–39.
120. Russell 2013: 53–61.
121. Cockle 1981: 87–97.
122. Aupert 1992: 362–63.
123. For Hadrian's focus on building projects involving sanctuaries and utilitarian infrastructure, see Chapter 9. For more detailed discussions, see Schorndorfer 1997: 19, 45–46, 57, 78, 118; Boatwright 2000: 204–09.

CHAPTER 4. COMPLEX VAULT FORMS OF BRICK

1. In the West, late examples (fourth century or later) also occur in some vaults and niches of the Aurelian Walls at Rome

(Vitti (2013 (pub. 2014)) and in a villa at Carranque, Spain (Fernández Galiano et al. 2001: 75).
2. Reuther 1938b: 501–02.
3. Boyd 1978: 94–96, fig. 11.
4. The pitched brick cross vault seems to have become common in the sixth century under Justinian, when it appears in cisterns in Istanbul (e.g., Binbirdirek and the Basilica Cistern). The only earlier example that I know of is one cited by Hoddinott (1975: 231–32, fig. 55) in a late third-century tomb outside Varna, but I have not seen it myself to check whether or not it actually has groins. For the example in the Aurelian Walls at Rome, P. Vitti (2013 (pub. 2014): 108–11) has shown that it belongs to a restoration under Justinian.
5. Oates 1970: 20–23, pl. 5a, Oates 1990: 402, fig. 7.
6. Besenval 1984: 131–32, pl. 172; Baimatowa 2008: 222–28, Abb. 188–93; Pugachenkova 1976: 130–31.
7. Leriche 2002: 113–25.
8. Besenval 1984: 139–40; Reuther 1938b: 502; Huff and O'Kane 1993.
9. Huff and O'Kane 1993.
10. Creswell (1969: 460–62 (cited by others)) gives early examples as the mausolea at Samaria (near Jerusalem) and at Qusayer an-Nuwayis (near Amman), and the West Baths at Jerash, but all date to the latter half of the second century or early third century CE.
11. Woolley 1934: 106, figs. 16–17, pl. 57a.
12. Junker 1941: 30–33, Abb. 3, Taf. 3.
13. Pieron 1908: 173–77; El-Naggar 1999: 310, fig. 385.
14. Boak 1935: 10–11.
15. Boak 1935: 12.
16. Boak 1935: 14, 37–47.
17. Husselman 1979: 67–69. Interestingly, Husselman (1979: 17) singled out these houses, which are clustered together in the same part of town, as being "unusually well built."
18. Petersen Manuscript (unpublished manuscript in Karanis Archive at Kelsey Museum at University of Michigan, Ann Arbor), p. 136.
19. Woolley 1934: 63.
20. Boak 1935: 37–47, esp. 37. The date of house I.103 is made on the basis of a papyrus dating to 74 BCE found in an adjacent house (Second Level) that was built above an earlier one contemporary with I.103.
21. El-Nassery et al. 1976: 257–59, pl. 37 fig. 12, pl. 40 figs. 18–19.
22. Hoddinott 1975: 231–32, fig. 55.
23. McKenzie 1990: 34, 41, 51. Schmid (2001: 382, 388) opted for a late first-century BCE dating for the Khasneh and Kasr el Bint. Stratigraphical excavations at the Khasneh suggest a date during the reign of King Aratas IV (9 BCE–40 CE), probably the latter part (Farajat and Nawafleh 2005: 388–89; Graf 2006; Khairy 2011), though Parr (2008) challenges the interpretation of the excavators, suggesting a date of mid-first century CE or somewhat later.
24. Kokkinos 1992: 280; Stone 1993: 370.
25. Bencivenga et al. 1979: 134, 150, fig. 55.1.
26. Lang-Auinger 1996: 134–35.
27. Lang-Auinger 1996: 26 n. 61, 135.
28. Lang-Auinger 1996: 205–06.
29. Thür and Rathmayr 2014: 57–58, 134.
30. Thür 2008: 1059.
31. *IvE* 4.1267; Thür 2002: 61–62; Zimmerman and Ladstätter 2011: 54, 78, fig. 70.
32. Mansel 1959: Bei. 383–85. The area is currently overgrown, but I was able to confirm the existence of a couple of the pour channels (June 2013).
33. For the use of iron tie bars, see Amici 1997; Hoffmann 1980: 26; Olivier 1983; Lancaster 2005a: 113–29.
34. Mansel 1959: Bei. 389–402, Mansel 1963: 186–87.
35. For portraits: Inan and Rosenbaum 1966: 193 (nos. 265, 266), pls. 144.1,3, 145.3–4.
36. For synopsis of dating: Cormack 2004: 300. For sarcophagi: Waelkens 1982: 77 no. 45, 83 no. 82; Wiegartz 1965: 171 (for c. 195 CE).
37. Kramer 1983.
38. Gliwitzky 2010: 140–57. Like Mansel, Gliwitzky argues for a later date for the outer enclosure based on the belief that the brick sail vaults did not occur before the third century CE.
39. Mansel 1960: Res. 3, Mansel 1963: Abb. 156; Sanpaolesi 1971: 54 fig. 70. See also the new reconstruction drawing by N. Karydis (2011: 92 fig. 105). The dome construction is represented more accurately than that of Sanpaolesi, but the niches have a more complex pattern (WebFig. 23) than represented in the drawing.
40. Mansel 1959: Bei. 366–74.
41. Butler 1922: 170–72.
42. Mansel 1959: Bei. 371.
43. Paus. 2.27.6.
44. Stamps: *IG* IV^2, 715–16. Melfi 2007: 248.
45. On date: Tomlinson 1983: 31. On Antoninus at Epidaurus: Melfi 2007: 248, Melfi 2010: 334–38. On Sextus Julius Maior Antoninus Pythagorus: Halfmann 1979: 171–72, Nr. 89. Inscription at Pergamum and relation with Aelius Aristides: Habicht 1969: 59 no. 23.
46. A third occurs in the church of St. Demetrius (at Thessaloniki Fig. 64B) and may be beyond the chronological parameters of this study, but the dating is problematic. Hoddinott (1963: 130 following Sotiriou and Sotiriou 1952) assigns it to the bath structure existing there before the fifth-century basilica was built, but I question whether the decorative nature of the vault could belong to a fourth(?)-century bath building.
47. Vitti and Vitti 2010: 278–83, figs. 14–17.
48. Chrysostomou 1982: 21 (English), figs. 1–2; Angeli and Katsadima 2001: 91–94.
49. P. Vitti's dissertation (Vitti 2013) is the most thorough study of vaulting in Greece thus far, but it focuses mainly on the Peloponnese. The published version is due soon: Vitti in press.

50. These dimensions are estimated from photographs that I took from the cornice level of the dome springing, but I could not reach the holes themselves to measure them. I thank Goran Nikšić, Head of the Service for the Old City Core, for taking me to examine the dome up close.
51. Hebrard and Zeiller 1912: 93; Nikšić 2004: 164–65.
52. This calculation assumes a brick 60 cm square, 4 cm thick, weighing 1750 kg/m³.
53. Zessin et al. 2010: 139–41.
54. The other large dome (11 m dia.) in the complex covered the vestibule leading into the mausoleum forecourt. Only the haunches remain, and they are built of small squared lightweight stones (*sedra*). The crown may have been built of radial brick similar to one in the substructures (WebFig. 22). See also descriptions in Werner 1981.
55. Knoll and Keil 1932: Abb. 54; Karydis 2011: 142–47.
56. For St. John at Ephesus: Karydis 2011: 101–05, 170–72.
57. Hoddinott 1963: 130, 134–37.
58. The Nysa vaults are not dated, but the theater remained in use until at least the sixth century (Kadioğlu 2006: 5), so they could well be Byzantine in date.
59. Philippi: Personal communication with Paolo Vitti and Carla Amici. Vodiča: Miljkovik-Pepek 1975: 70, pl. 21. I am grateful to Robert Ousterhout for identifying this vault from St. Leontius from an unlabeled photograph.
60. Bernard 1994.
61. Suet. *Aug.* 18.
62. Schmid (2001: 370–88) provides a very useful overview of the development of Petra, with a relevant bibliography for specific categories of evidence.
63. Heron, *Stereometry* 2.2.
64. McKenzie 2007: 324.
65. For a discussion of the relationship of Alexandrian mathematics to architecture, see Napolitani and Saito 2013.
66. Thonemann 2011: 154.
67. Mansel 1959: Bei. 389–90. See also Gliwitzky 2010: 140–57 for a reassessment of the evidence for Mansel's reconstruction.
68. Fontenrose 1988: 193–94; Buckler 1923: 35.
69. *CIG* 2782. Chaniotis 2008: 72–73.
70. Const. Porph., *de adm. imp.* 29. 243, 252, 254, 271, 282, 284. For English translation and commentary, see Moravcsik and Jenkins 1967.
71. Hellman 1988: 258.
72. Herrmann 1998: 121–22.
73. Robert (1968: 581 n. 4) suggested that the problems could have originated from the death of Ulpianus, the workers' superintendent.

CHAPTER 5. VAULTING TUBES

1. Vaulting tubes are known as *tubi fittili* in Italian, *Tonröhren* in German, *tubes de voûte* and *tubes emboîtés* in French, and *tubos afusados* in Spanish.
2. Lugli 1957: 689; Giovannoni 1925: 38; Rivoira 1925: 263.
3. Lancaster 2005a: 68–85.
4. Examples occur in the Casa de la Esedra at Italica (Fig. 16); at the *fabrica* at Chemtou: Khanoussi et al. 1994: Taf. 81–82; House of the Treasure at Bulla Regia: Wilson 1992: 109 fig. 16; and in the Harbor Baths at Elaeussa Sebaste: Spanu 2003a: 299–330, esp. 308 each from the second/third century CE.
5. Allen 1974.
6. Lucore 2009: 46–49.
7. S. Lucore: Personal correspondence.
8. Cultrera 1938: 286.
9. Martín (2000: 159–60) notes that a "*cúpula*" was used over the *tepidarium*, but how this was accomplished given the square shape is not clear.
10. Martín 2000: 159–60.
11. Bouet 1999: 114.
12. Wilson 1992: 108.
13. Lucore 2009: 46.
14. Storz 1994: 4–5, 10; Wilson 1992: 107–08.
15. Brecciaroli Taborelli 1998: 61–65, figs. 41–42.
16. Marcianella: Mascione and Aprosio 2003: 263–70; Mascione 2003: 51. Ordona: Mertens 1985: 73, 76 n. 3, fig. 6; Deru and Paicheler 2000: 438, figs. 404.1–2. Massa: Cerato et al. 2012. Ca Lo Spelli: Menchelli et al. 2013.
17. Cuomo di Caprio 1992: 65 n. 121.
18. Laubenheimer 1990: 104–08; Stoppioni 1993: 35–36, 109; Heising 2007: 35, 60, 89.
19. France: Laubenheimer 1990. Pompeii: Cerulli Irelli 1977. Po Valley: Stoppioni 1993. Germany: Dusek 1992; Heising 2007.
20. For the proposal concerning reeds: Cintas 1953: 257–58; Lézine 1954: 180; Allen 1974: 377–79.
21. Wilson (1992: 111) discusses the evidence from Rome presented by R. Bergau (1867) in the nineteenth century for various small pots that he thought could have been used for vaulting, but as he notes, the contexts for establishing use and dates are not clear. In fact, all but one of Bergau's pots belong to a curious type of small vessel that probably did not relate to vaulting. C. Pavolini (1980) has discussed a group of similar ones at Ostia and explored possible other functions, such as amphora stoppers, gaming pieces, or lamps.
22. Herculaneum gate: Fulvio 1879: 280–81, tav. 2.2; Overbeck 1884: 380; Durm 1905: 299, fig. 326; Annecchino 1977: 106. Via Nocera: Cuomo di Caprio 2007: 511, fig. 16; Cerulli Irelli 1977: 55–57, 70–71 figs. 3, 8.
23. Scurati-Manzoni 1997: 9–11, for the variation in size, see figs. 7–8.
24. Tomasello 2005a: 143–45, fig. 63, 199–200, Tomasello 2005b: 145–48.
25. Storz 1994: 29–31.
26. Storz 1994: 32, Taf. 3.3.
27. An example of a fully developed nozzle tube from Mozia, Sicily, was originally published as coming from a first-century

BCE context, but in a later publication the excavator noted that, in fact, the context had been disturbed: Tusa 1970: 10–11, Tusa 2000: 1401.

28. Lézine 1954: 180, fig. 11. Wilson (1992: 104) questioned whether it can be assumed to have a firm date in the early second century.
29. Bulla Regia: Khanoussi 1983: 96 n. 23, 99, fig. 24. Tipasa: Lancel 1970: 208, fig. 61.11.
30. Norman and Haeckl 1993. I thank Naomi Norman for sharing information with me about these vaulting tubes.
31. Mackensen 2005: 100–01, 122; Khanoussi et al. 1994: 135, Abb. 65–66, Taf. 81b–c, 82b–c.
32. Storz 1994: 66 n. 174.
33. Inscription: Poinssot 1958: 21, 29–30. Lézine 1961: 153 n. 2.
34. Fentress 1979: 161–71; MacMullen 1959: 214–17.
35. Rakob (1995: 40–41) originally saw it as part of a military complex, but more recent excavations have shown that the easternmost building, which is considered the military camp, was added only in the mid-third century, and Mackensen has called into question any permanent garrison at Chemtou (Mackensen 2005: 119–22 (English summary of new excavations).
36. Khanoussi in Beschaouch et al. 1993: 68.
37. *IRT* 913; Goodchild 1954: 60; Rebuffat 1976–77: 44–47, pls. 16–17.
38. *CIL* 8.17727, 17728; Saxer 1967: 104.
39. Gsell and Graillot 1893: 507–17 esp. 511 (portico), 513 (dome), Taf. 8 (plan).
40. Mason 2005: 36. In his initial report, Mason (1990: 217) described the fallen vault as having been built on hollow voussoirs (*tubuli cuneati*), but he later revised this assessment, noting that the archive material showed that box-tiles from the walls had become mixed with the vault debris (Mason 2005: 57 n. 2). He speculates that hollow voussoirs were used in the earlier Flavian phase of the building and shows them in the reconstruction (Mason 2005: 40, fig. III 40), but no example has been found at the site.
41. Mason 2000: 136.
42. Legionary Baths at Caerleon: Zienkiewicz 1986: 107–12, 334–36, fig. 111, nos. 18–21. Castle Baths at Caerleon: Zienkiewicz 1986: 335, fig. 111, nos. 22–24. York: Whitwell 1976: 45, no. 23.
43. R. J. A. Wilson 2002, Wilson 2003.
44. Mason 1990: 222, Mason 2005: 38. For an early third-century date at Caerleon, see Zienkiewicz 1986: 335–36. For military connections and vaulting tubes, see also R. J. A. Wilson 2002, Wilson 2003; Storz 1994: 66.
45. Swan 1992.
46. Brown 1936: 50, 61, pl. 14.1; Downey 2000: 169; Perkins 1973: 25 and n. 1; Pollard 2004: 132–43; Storz 1994: 66.
47. Brown 1936: 77–80.
48. Pollard 2004: 142–43; *RE* 12.2: 1499–1501 s.v. "Legio."
49. Brown's (1936: 50) description of the vault fragment is difficult to interpret, and I have not examined the vault fragment myself. He concluded that the fragment belonged to the haunch of the middle pier just above the springing.
50. Brown 1936: 49–50, pl. 3 (plan and section).
51. Bosnia Herzegovenia: Bojanovski 1980: fig. 8. Serbia: Jeremić 2006: 88–90, figs. 9–11, 13. Romania: R. J. A. Wilson 2002: 182 citing John Hayes.
52. Pompeiopolis: Koch 2011: 65, Taf. 5.3. Hungary: Buday 1914: 63–66, figs. 3, 8, 12.
53. Carandini 1970: 97–119.
54. For overview: Lewit 2011–. For connection with agriculture: Lancaster 2012a: 151–60.
55. Kehoe 1988: 29–48.
56. Kehoe 1988: 55–63.
57. Hitchner 1995b: 143–57. Whether the *lex Manciana* applied to non-imperial lands is debated, but Hitchner (1995a, 1995b: 141) and Kehoe (1984) have argued it was likely applied to private holdings as well.
58. *CIL* 8.212; Groupe de recherches sur l'Afrique antique 1993: 251–56.
59. *CIL* 8.11824 = *ILS* 7457.
60. De Romanis 2003: 704–07. Sitifis: *CIL* 8.10363. Cirta: *ILS* 5872, 5873 (*per possessores territori Cirtensium*). Simitthus to Thabraca: *CIL* 8.10960 = 22199.
61. On the importance of road building for economic growth and connectivity, see Hitchner 2012: esp. 228–30 for Africa Proconsularis.
62. *CIL* 2.1180 = *ILS* 1403. Oil may have been added as early as the 140s: Peña 1999: 20–21.
63. Along the east coast, production of amphoras has been identified at ancient sites of Neapolis, Hadrumetum, Leptiminus, Sullecthum, and Thaenae through excavations of production sites and stamps on the amphoras. Sites in Byzacena: Mattingly 1988: 45–48; Peacock et al. 1989. Leptiminus: Stirling and Ben Lazreg 2001: 229; Stone 2009. Neapolis: Slim et al. 2007. For the contents of various amphora types: Bonifay 2004: 463–75.
64. Bonifay 2003: 115.
65. Mackensen and Schneider 2006: 173.
66. Mackensen and Schneider 2006: 179.
67. Lewitt (2011, 2013) has examined the terra sigillata industries in southern Gaul and in North Africa from a similar perspective and emphasizes the importance of the confluence of factors, including fuel sources, state-sponsored transport, agricultural production, and natural resources.
68. Olivier and Storz 1983: 125.
69. The bodies of the tubes at San Vitale are about 14 cm long and 6 cm in diameter, which yields 84 tubes per m^2. The dome has a span of 15.6 m with an intrados area of 382 m^2. The dome comprising the second layer of tubes has a diameter of 16 m with an intrados area of 402 m^2. These figures ($84(382 + 402)$) give a total of 65,856 tubes.
70. Mason 2005: 52.
71. Storz 1994: 33.

72. For the turning of African sigillata, see Peña 2009.
73. Fentress 2009: 173, fig. 10.48.
74. Mackensen and Schneider 2002: 150.
75. For firing of different types of wares in the same kiln, see Barraud et al. 1998: 165. Bonifay (2004: 86) suggests that vaulting tubes were fired with amphoras and common ware.
76. Bonifay 2004: 73.
77. Mackensen 2009: 38.
78. Stirling and Ben Lazreg 2001. They cite an even larger kiln (5.5 m int. dia.) found in Aïn Scersciara, Libya.
79. Parker 1992: 99, 168, 173, 271; Wilson 1992: 129.
80. Storz 1994: 35–37; Wilson 1992: 119–20.
81. Santamaria (1995: 67–68) reported thirty tubes from the Dramont E wreck (420–425 CE) and believed that they cannot be considered cargo.
82. Bound 1987: 196–97. For the distinctive creamy surface on North African pottery, see Peacock 1984b.
83. Royal and Tusa 2012: 22–23, 44.
84. Bound 1987: 192; Wilson 1992: 120.
85. Lézine 1954: 169.
86. Bound 1987: 190–91; Peacock 1984a: 245; Mason 1990: 220.
87. Lugli 1957: 689; Giovannoni 1925: 38; Rivoira 1925: 263; Brodribb 1987: 87.
88. Bound 1987: 190–91; Mason 1990: 220.
89. Storz 1994: 67; Mason 1990: 220 citing Ward-Perkins 1977: 152.
90. Lézine 1954: 178–79.
91. See also Wilson 1992: 109.
92. Lézine 1954: 178; Storz 1994: 68.
93. For discussions of deforestation in North Africa: Shaw 1981: 391–93; Ballais 2000. Meiggs (1982: 399–401) discusses the abundance of forest in various parts of North Africa, but his focus is on the Punic and Republican periods using sources such as Strabo, who was writing much earlier than the period when the tubes were used.
94. Tert., *De anim.* 30.3.
95. Peacock 1982: 25; Stirling and Ben Lazreg 2001: 228; Smith 1998; Barraud et al. 1998: 145.
96. DeLaine 2002.
97. Setälä 1977: 34–37.
98. Kehoe 1984: 250–63.
99. Graham 2011: 481–82 and references therein.
100. I thank Miles Lewis for bringing my attention to the tubes in the substructure and supplying me photos. I had only found those with the reed mats on my own inspection.
101. Broise and Thebert 1993: 310–16.
102. The House of Fishing is the only house with underground rooms built on wooden centering (Thébert 1972: 30). Other houses with underground rooms built on tubes are the House of Amphitrite, House of the Hunt, New House of the Hunt, House of the Treasure, House of the Peacock, and Houses 1, 2, & 3.
103. Thébert 1972: 40; Bullo and Ghedini 2003: 40.
104. Bullo and Ghedini 2003: 33–72.
105. Bonetto 2003: 295.
106. Storz (1994: 44, Taf. 10) explains the process his team employed in reconstructing one of these vaults.
107. Thébert 1987: 344, 350. He does not elaborate on the nature of the earlier structures. In some other houses, such as House 1, the basement was remodeled from preexisting cisterns (Thébert 1972: 23–24, 28–29).
108. Entry portico: Poinssot 1958: 21, 48; Storz 1994: 74–75 n. 10, 78.
109. Golvin and Khanoussi 2005: 145–47.
110. Storz 1994: 48, n. 265, 68–69.
111. Storz 1994: 77 n. 25.
112. Bullo and Ghedini 2003: 273. Storz (1994: 68, Taf. 29.1–2) also notes an eight sided composite sail vault at the Baths of the Cyclops at Dougga.
113. Storz 1994: 50–52.
114. Storz 1991: 57.
115. Storz 1994: 69.
116. Cante 2004: 20–21, 24 fig. 35. The tubes were not found in situ, but nearly 300 examples were found in the portico excavations.
117. Sanctuary of Syrian Gods: Gauckler 1912: 191–92, fig. on p. 191 (tube), pl. 51 (plan); Meneghini 1984. Basilica Ursiana: Bovini 1960: 80; Russo 2003: 5–6; Deichmann 1976: 8, Abb. 12. Hippo Regius: Gsell 1901, 2; 139; Marec 1958: 27. Sufetula: Duval 1971: 27, 76–80.
118. Lucore 2009.
119. Lucore 2013: 171–72; Napolitani and Saito 2013.
120. Gandolfi 1994: 129.
121. Bullard 1978: 21. For the area around Dougga, see De Vos 2008: 274–75. For geological explanations of the formation of Tunisia, see Martin 1967.
122. I thank Hansgeorg Bankel for bringing the Nazi vaulting tubes to my attention and Manfred Deiler for sharing with me his research on Kaufering VII and its vaulting tubes (Deiler in press) See also www.buergervereinigung-landsberg.de/gedenkstaette/kaufering7.htm (last accessed June 16, 2015).
123. A video of the construction is available on the Rural Housing Knowledge Network on YouTube at www.youtube.com/watch?v=rA-0OcYYTVc (last accessed June 16, 2015).

CHAPTER 6. HOLLOW VOUSSOIRS

1. The only other documented examples of roller stamps occur on a small group of flat tiles found in Germany from second-century CE contexts: Baatz 1988; Betts et al. 1994: 46.
2. Russell 1991: 87–117, Russell 1994: 47–50.
3. The earliest example of roller-stamped daub I have found dates from the early first century CE at Cologne: Thomas 1993: 277, Abb. 115. Others include Strasbourg, France: Barbet and Allag 1972: 952–53; Ehls, France: Hatt 1968: 419 fig. 14, 421; Narbonne, France: Sabrié et al. 1987: 248, fig. 227; Hofheim, Germany: Ritterling 1913: 43 fig. 13;

Bonn, Germany: Fiedler and Höpken 2012: 52–55, Abb. 1–2; and Braives, Belgium: Brulet 1981: 188 fig. 78.

4. Formula: Span = 2((bc)/(a-b)) from Woods 1966: 20–21. Brodribb 1987: 79 attempts to give the formula, but evidently there was a printing error and the second half of the formula is missing.
5. Bridger 1989: 55, 63.
6. Yegül and Couch 2003: 175, fig. 26.
7. Sen. *Ep.* 90.25. His comment accords well with M. E. Blake's (1959: 67, 163) reference to an early example at the Terme della Via dei Vigili at Ostia (2.3–4), dated to the Claudian period in the first half of the first century CE.
8. Pompeii: Schween 1936: 23; Eschebach 1979: 14; Jorio 1978–79: 179. Herculaneum: Maiuri 1958: 150, 162–63, 165; Jacobelli 1987: 152–54.
9. Baths at Kyaneai, Turkey: Farrington and Coulton 1990: 59. Villa baths at Grand Loou I in La Roquebrussanne, France: Bouet 1999: 24, 32. Here the *mammae* were less than 2 cm high. The main reason for thinking that they were applied to the vault is that they were long and narrow, which would have allowed them to follow the curvature. See also Chapter 7, note 17.
10. See experimental baths at Sardis: Yegül and Couch 2003: 175, fig. 26.
11. Exeter: Bidwell 1979: 13–17, 32–33, 148–51. London: I. M. Betts (MoLAS), personal communication. Caerleon: Zienkiewicz 1986: 37–38, 74, 327–29, fig. 108.1.
12. Hills 1868: 212–15, fig. 6.
13. The fabric is defined as Museum of London fabrics 3054 and 3059. Type 3054 includes abundant quartz (<1 mm) and grog of cream and red tile fragments (<6 mm); 3059 is the same as 3054, but with organic chaff tempering leaving burned-out voids (Betts et al. 1994: 19). The London Sussex Group was identified by E. Black (1985: 356) and includes dies 19, 20, 21, 22, 23, 24, 37, 40, 60, 81, 83, 86, 87, 95, 96, 109, 111, 112, and 113 (Betts et al. 1994: 19).
14. Betts et al. 1994: 52. Their production also included single flue box-tiles (Betts et al. 1994: 91), a type of *tegulae mammatae* for flooring (Pringle 2009: 196), and occasionally bricks.
15. Betts et al. 1994: 52.
16. For an overview of the dating criteria with further references, see Lancaster 2012b: 424.
17. Scott 1938. For the history of excavations and more recent discussion of the dating, see Gilkes 1998, Gilkes 1999.
18. Lancaster 2012b: fig. 7.
19. Black 1985: 356, Black 1987: 88.
20. For a more detailed discussion of this bath and the Westhampnett voussoirs, see Lancaster 2012b.
21. For a photograph of all three tiles, see Lancaster 2012b: fig. 12. Thanks to I. M. Betts for his observation on the tile fabrics found at Bath. The fabric of the one at Colchester has not been examined to my knowledge.
22. For illustration, see Lancaster 2012b: fig. 13.
23. Three other cases suggest that the tiles of the Sussex tile makers began to be imitated by others, though none is a voussoir. In two examples, at Upmarden and Lavant, tiles bearing dies (87 & 96) from the London-Sussex group were used in a different fabric, which suggests that "the dies were used in more than one tilery" (Betts et al. 1994: 20). At Ashstead villa a variant of the double flue box-tile at Angmering was found without roller stamping (Lowther 1931: 146–47). However, the same variant was found at Eastbourne villa along with a Westhampnett voussoir, both of which were stamped with die 19 (Betts et al. 1994: 91; Sutton 1952: pls. 1, 5b; Harcum 1925: 287 fig. 7), thus suggesting that the Ashstead example is a later imitation, probably Hadrianic (E. Black, personal communication).
24. Betts et al. 1994: 35.
25. Yegül and Couch 2003: 169, 175.
26. In quantitative terms, the thermal resistance (R-value) of an airspace reaches its maximum efficacy ($R = 0.176110$ $K{\cdot}m^2/W$) at a thickness of only about 3 cm; at any greater thickness the radiant benefits are canceled out by the effect of convection (Beall 1999: 80). The thermal resistance of concrete, in contrast, increases constantly in direct proportion to its thickness; therefore a 13 cm thick layer of mortar or concrete would have an R-value roughly equivalent to a 3 cm airspace (assuming concrete with a thermal conductivity value (k) of 0.75 W/mK where R = d (thickness)/k), but doubling that thickness (d) would also double the R-value so that it would be twice as effective as an airspace; therefore the concrete offers greater insulation potential. I thank Eric Burgmann, a thermodynamics engineer at General Electric in Cincinnati, for sharing with me his insights and advice on this issue.
27. Blockley et al. 1995: 191–92, fig. 97 (plan), pl. LVIII. They make a distinction between "voussoir tiles" and "loose tiles," so presumably the latter refer to *tegulae*.
28. Davis 1884.
29. Cunliffe 1969: 111, 133, fig. 48.
30. Kienzle 2010: 88–89, figs. 104, 106.
31. Warry 2006: 110-18. I am grateful to Peter Warry for sharing his database of convex *tegulae* with me.
32. Gilliam et al. 1993: 14.
33. Brodribb 1987: 83.
34. Canterbury: Black 1995: 1275–76. Beauport Park: Brodribb 1979: 147–48.
35. Ellis 2000: 49, 356, fig. 6.11; Fox 1897: 147–49.
36. Black 1995: 1275–76.
37. Yegül and Couch 2003: 175.
38. Kienzle 2010.
39. *CIL* 10.3687 = *ILS* 5689; Blyth 1999: 87.
40. Labitolosa: Magallón and Sillières 2013: 178–80. Coudoux and La Garde: Bouet 2003a: 248. Bulla Regia: Broise and Thebert 1993: 339.
41. Scott 1938: 44.
42. In a previous publication (Lancaster 2012b), I suggested that charcoal reported from Angmering may reflect a desire for fuel efficiency on the part of the patron, but given the more recent body of evidence cited here, I have become more

circumspect about this idea and believe that further evidence from other hollow voussoir baths is necessary to test it.

43. Rudling et al. 1986.
44. Middleton et al. 1992: 54.
45. Betts et al. 1994: 33, fig. 18.
46. Betts et al. 1994: 103.
47. Betts et al. 1994: fig. 19.
48. Black 1995: 1275, 1279.
49. Betts et al. 1994: 44; Davies 2004: 169–70.
50. Betts et al. 1994: 154. Betts (2008: 164–65) identifies it as a new die.
51. North Africa: Mackensen 2009: 38. Gaul: Peacock 1982: 125–26.
52. Black 1985: 358.
53. For the kiln, see McWhirr 1979: 181–82.
54. Betts et al. 1994: 33–35.
55. Betts et al. 1994: 102.
56. Betts et al. 1994: 51.
57. I owe this idea to J. Kenney.
58. Frere 1977: 388.
59. Black 1995: 1275, 1279. For the collapsed hollow voussoir vault, see Blockley et al. 1995: 191–92, fig. 97 (plan), pl. LVIII.
60. Petit 2000: 81–82, 177.
61. Baatz 1988. For a summary, see Betts et al. 1994: 46.
62. Cunliffe 1973: 165.
63. Tac., *Agr.* 14.
64. Tyers 1996: 89 fig. 55.
65. Tac., *Agr.* 14; *RIB* 91.
66. Cunliffe 1973: 79, Cunliffe 1991: 165.
67. Betts et al. 1994: 44; Tomlin 2012: 421; *RIB* II.5: 2491.84.
68. *RIB* II.5: 2491.126. I thank R. S. O. Tomlin for his suggestion of the reading "Titus Flavius" and its significance.
69. Marichal 1988: 29.
70. Tomlin 2012: 411. For other Celtic names beginning in Bel-, see Raybould and Sims-Williams 2007: 42–43. For the use of the *cognomen*, Bellicus, by a Roman citizen of probable Gallic origins in Kent, see Tomlin 1996: 214.
71. Lancaster 2012b: 435.
72. Seeley 2012: 243.
73. Tyers 1996: 66, fig. 38.
74. Betts et al. 1994: 33–34.
75. Caesar, *BG* 5.12.7. I thank E. Black for pointing me to this reference.
76. See Creighton 2006: 55–69, 157–61, who argues for more precocious adoption of Roman habits.
77. Tyers 1996: 58. Down 1978: 56–58.

CHAPTER 7. VAULTING RIBS OF ARMCHAIR VOUSSOIRS

1. They are also referred to in English as *flanged bricks*; in Italian as *mattoni da nervatura*; in French as *briques (claveaux) à tenons*, *briques à crochet*, *voussoirs à encoches*, or *tuiles à épaulement*; in Spanish as *ladrillos (dovela) con resaltes cuadrados* or *ladrillos de entalle*; and in Portuguese as *tijolo con recortes*.
2. France: Bouet 1999; Fincker 1986. Britain: Woodfield and Johnson 1989; Brodribb 1987. Iberia/Morocco: Ponsich 1970: 378–80; Camporeale 2008b; Torrecilla Aznar 1999; Pérez Losada 1992.
3. Tsiolis 2001: 106–08, Tsiolis 2006: 246, fig. 5, Tsiolis 2013: fig. 6. Without further information on the number of bars found, the sizes and details of each of the four types, and a more precise description of the holes and grooves containing the lead, it is difficult to assess the details of the reconstruction shown in Figure 103.
4. Tsiolis 2001: 89–90.
5. Tsiolis 2001: 87–88, Tsiolis 2013: 111 n. 39.
6. Tsiolis 2013.
7. A preliminary publication of the kiln site has been published (Cerato et al. 2012), but the terracotta bars have not. Information here is presented courtesy of E. Parabeni and E. J. Shepherd, who plan to publish further detailed information on the bars.
8. Iannelli and Cuteri 2013: 141 n. 19, fig. 13.
9. Shepherd 2008: 51–57 (date), 188–200 (armchair voussoirs and bath tiles). On finds of armchair voussoirs in Florence: Shepherd 2015: 185–86.
10. Rodà 2013: 535. Baetulo was established at some time during the second quarter of the first century BCE, after the Sertorian War (80–73 BCE) when a number of cities were established under Pompey.
11. Guitart Durán 1976: 76–78; Guitart Durán and Padrós Martí 1990: 169–72.
12. These H-type bricks (12–15 cm square) have been found at three military sites – in the Netherlands at Nijmegen and in Germany at Xanten (Hanel 1995: 276–277) and Nuess (Lehner 1904: 311, Taf. 21.3). Their small size makes me question if they were used for vaulting. I am grateful to Tim Clerbaut for this information.
13. Bouet 1999: 88 fig. 50, 92 fig. 54.
14. Charmasson 2003: 140, fig. 16; Bouet 2004: 213.
15. Charmasson 2003: 160–72; Bouet 2004: 226, 229.
16. Dating of baths: Bouet 2003b: 138. Dating of voussoir: Bouet 1999: 91, 113). It is unclear how many of the voussoirs were found.
17. Remains of *tegulae mammatae* were also found, but they belong to the type with very small *mammae* (2.2 cm) and were not used for heating the walls. Bouet (1999: 24, 31–32, fig. 7) concludes that this type of *tegula mammata* may have served as protection from dampness. These bricks with very small *mammae* are also often found in Britain, as documented by Brodribb, who also concludes that they must have had a function other than for heating (Brodribb 1987: 60–62, 148–49). At the recent conference "Arqueología de la construcción 5" in Oxford (April 2015), G. Overbeek and T. Clerbaut presented similar examples from northern provinces

of Gallia and Germania Inferior, and they proposed that the small *mammae* were used as spacers during the firing process.

18. For dating, see Di Vita 2004 (pub. 2006): 691–97.
19. Fournet 2011.
20. Boyd 1978: 97, fig. 13.
21. Naumann 1937: 22–29.
22. Gros 1984; Gans 1990; von Hesberg 1981–82: 67, 82.
23. Naumann 1937: 24–29.
24. Anderson 2013: 172–74; Thomas 2007: 50.
25. The "Temple of Diana" is a barrel-vaulted public building of some status, and nothing like it is known from the Augustan period in Rome or elsewhere. Vaults with comparable spans during the late Republic and early empire tend to be in utilitarian structures (substructures of the Sanctuary of Hercules at Tivoli and the "*Porticus Aemilia*" at Rome), baths (Stabian and Forum Baths at Pompeii), gateways (Arch of "Trajan" at Mérida), bridges, and aqueducts, whereas in the second century CE, vaults began to be used as a means of adding prestige to public venues such as temples (Hadrianeum in Rome, Argos cult room) and libraries (Bibliotheca Ulpia in Rome).
26. Imperial cult: Gros 1984: 128–29. Library: Anderson 2013: 172–74.
27. Magallón and Sillières 2013: 274.
28. Woodfield and Johnson 1989: 249–51.
29. MacDonald (1931).
30. The voussoirs of the "Temple of Diana" also have holes in the center of the bearing faces, but without closer examination it is impossible to determine their purpose.
31. Vitr. *De arch*. 5.10.3 (Trans. F. Granger, Loeb, 1931).
32. *Structura* can also be translated simply as "masonry." For Vitruvius's use of *structura*, see Lugli 1957: 45–46.
33. Shepherd 1989: 419–31 noting also that a similar system was excavated at Fiesole (with bibliography).
34. For other examples of hanging tile vaults, see Shepherd 1989: 422. The technique was also used for large spans at Fontaines-Salées baths at Saint-Père-sous-Vézelay in France over two heated pools, one circular and one rectangular with spans of 9 m and 7 m, respectively (Louis 1938: 259–63, fig. 12, thanks to C. M. Amici for this reference).
35. Chabal 1993. Bouet (1999: 103) includes this example in his catalog with thanks to the excavator, but it is not documented in the excavation report (Monteil and Recolin 1993), so the context of its discovery is unclear.
36. Biers and Biers 1988: 98.
37. Magallón and Sillières 2013: 146, 176, 282–85.
38. Monturet and Rivière 1986: 174–75, 250–51. The armchair voussoirs were found in fill of rooms 5, 20, and 21 when they were remodeled in the fourth century and reused as hypocaust piers in late fourth-century phase of room 20 and late third-century phase of room 13.
39. Bouet 2003c: 178–80, 397 fig. 9.
40. Bouet 1999: 111.
41. Fincker 1986: 145, fig. 2.
42. Benoit 1977: pl. 11 fig. 21. Bouet (1999: fig. 55b) provides his own measured drawing of one of the voussoirs, which suggests that he has examined it (?), but I have not.
43. "De grands segments de ces doubleaux comprenant les briques à crochets et les briques de couvert en place, dont *l'intrados* avait encore conservé l'enduit de chaux du berceau, ont été trouvés avec leur lit de béton dans leur position de chute." (Benoit 1977: 61). The same ambiguous phrasing is in the original publication (Benoit 1958: 442).
44. Benoit 1977: pl. 10 fig. 17, Benoit 1958: fig. 40.
45. For the Fréjus vault, Textier (1849: 204) reported the width of the room as 10 m, but it measures slightly less on his plan (pl. VI). The wall opposite the standing wall no longer exists for an accurate measurement. There is no modern publication of the standing wall, but Textier (1849: pl. VI) provided a measured drawing and Bouet (1999: fig. 49b) includes a photograph of the vertical channels in which the armchair voussoirs were housed.
46. Cimiez is unusual in having three large baths located together, one next to the other. Absolute dates are not clear, but the relative dating puts the North Baths first, followed by the East Baths, and finally the West Baths. Recent excavations in the East Baths, along with reexamination of the stratigraphy of the pottery finds from the original excavations in the 1940s, have served to move its date from the second half of the third century (assigned by Benoit) to some time in the late first century or during the second century. This in turn moves the construction of the North Baths from the first half of the third century to some time earlier than the East Baths (Ardisson et al. 2007: 50, Ardisson 2011: 327 n. 8; Grandieux 2007). The details of some of these arguments are in publications that I have not been able to access.
47. A date for the Fréjus baths in the second half of the second century was proposed by C. Gébara based on the excavation of a drain just outside the complex that probably connected to the *natatio* and on analogies of the use of *opus vittatum* elsewhere at Fréjus (Gébara and Béraud 1990: 9; Gébara 2012: 201). Ardisson (2011: 324) notes that, based on sculptural finds at the Porte d'Orée baths, there is discussion of a date as early as the Flavian period when the port was upgraded, but Gébara points out that sculpture can be reused and does not provide the basis for a valid dating for the building itself.
48. Bouet (1999: 113) cites early examples of Type 3 from Limoges (90–120 CE), Montréal, and Taradeau (both during the first half of the second century), but he does not mention the early (Tiberian) example of a Type 3a voussoir (double slab) at Olbia or the Type 3a found at Gaujac.
49. Benoit 1977: 67–69.
50. Camporeale 2008a: 134 n. 128, 136–37. The dating of this phase of development within the city is based on the dating of the new fortifications.
51. Roldán Gómez and Bernal Casasola 1998: 350–51, fig. 256; Roldán Gómez 1999: 186. A drawing of the grooved-type

brick is provided in Roldán Gómez 1992: 112 fig. 28, but with further discussion.

52. Torrecilla Aznar 1999: 409.
53. Torrecilla Aznar et al. 2002: 263, fig. 150. Given that the rebates have no function in a wall brick, they must belong to the topside of an armchair voussoir.
54. Magallón and Sillières 2013: 157–58, figs. 39a–b, 49, 51a–b.
55. Magallón and Sillières 2013: 269–72, 294–95, figs. 19–20, 22, 25a–c.
56. Biers and Biers 1988: 108–16.
57. Camporeale 2008b: 188.
58. Torrecilla Aznar 1999: 408.
59. Tongobriga: Tavares Dias 1997: 133–34.
60. The use of the notched brick as a 42 cm inner lining would have reduced the width of the *tepidarium* to 4.05 m, a 17% decrease, which seems wasteful in terms of both material and space. The typical airspace using box tiles, *tegulae mammatae*, or spacers rarely exceeds 12 cm, so a 42 cm wall with flues would be extraordinary. Moreover, the reconstruction does not show how the hypocaust would be connected to any of the flues: those inside the piers or those between them (Tavares Dias 1997: 133–34, 224). Without further information on the context and findspots of the individual bricks, the viability of the proposal is difficult to judge.
61. The Constantinian Basilica at Trier has vents remaining where the box-tiles vented (Lehar 2012: 99–100, Abb. 113–15). Bath 1 at Labitolosa has well-preserved vents that allowed hot air into the base of the vertical channels carved into the walls (Magallón and Sillières 2013: figs. 49–51).
62. Biers and Biers 1988: 98, 103, 208–09.
63. Bouet 2003a: 328; Marzano 2013: 112–16. Many of the examples of the armchair voussoirs occur in villas with baths dating back to the Flavian period, but the baths were often modified so that associating the tiles with particular phases is not possible: Le Chateau villa at Rouffiac (Flavian period to the second half of the second century), Brachaud villa at Limoges (90–120 CE, hypocaust (?) arch), Liégeaud villa at La Croisille-sur-Briance, Saint-Romaine villa at Loupiac, Anzas villa at Sainte Colombe de Duras, Lassales villa at Montmaurin (early second–third century examples used in fourth-century hypocaust wall), La Domergue villa at Sauvian (no chronological data), La Clémensanne villa at Taradeau, Muscapeù villa at Tourves (WebCat. 7-A).
64. Bouet 1999: fig. 112.
65. For Clarianus box tiles, see Bouet 1999: 42.
66. Bouet 1999: 185–86. For Clarianus, see also Aubert 1994: 238–39.
67. Bouet 1999: 106–13.
68. Tremoleda 2000: 183, fig. 129; Barti et al. 2004: 128–30.
69. Tremoleda 2000: 183, fig. 129, Tremoleda 2000: 181–84, 220. SEC (*tegulae*), PRI (retro) (*tegulae*), HERMES (*tegulae*, *imbrices*), MVL (flat tile), P VSVL VEIENT (*tegulae*, Pascul 1 amphora).
70. Tremoleda 2000: 183.
71. Tremoleda and Castanyer 2013: 493–94.
72. Tremoleda 2000: 184–85.
73. Bainton and Durobrivae: Challands 1975: 21, fig. 9. York: Woodfield and Johnson 1989: 252.
74. Brodribb 1983: 109.
75. Purdy and Manby 1973: 101–02, fig. 3; Brodribb 1983: 108.
76. Bidwell 2005: 36.
77. I thank S. Pringle and I.M. Betts of the Museum of London for supplying me with this unpublished information. The Eccles villa continued production into the second century when it made hollow voussoirs bearing stamps of die 12 (Betts et al. 1994: 80, 81-82).
78. This example was cited by Woodfield and Johnson (1989: 252), but I have no further documentation of it.
79. Bernal et al. 2013; Bernal et al. 2014: 471.
80. Ponsich 1970: 265–71, 302; Camporeale 2008c: 204.
81. Warry 2010: 142.
82. Camporeale 2008c; Gliozzo et al. 2011.
83. For a discussion of the relationship between military and civilian tile production, see Kurzmann 2006: 232–41.
84. Étienne and Mayet 1971: 66–67, fig. 4.
85. Ponsich 1970: 271, 350, 380, 386; Étienne and Mayet 1971: 66–68 following Ponsich. The IMP AVG stamps were also found in a small bath that was built into one of the towers of the military camp at Gandori (late third to early fourth century CE), which also led to the assumption that they were late.
86. Sillières 1995: 161–62; Arévalo and Bernal 2007a: 51–55, Arévalo and Bernal 2007b.
87. Steinby 1986: 103–09. The distinction between the imperial *patrimonium* (personal wealth of emperor) and the imperial *fiscus* (government revenue) changed over time, but both are distinct from the *res privata* (personal family wealth).
88. Woolf 1998: 182–85.
89. Brun 2005.
90. Bouet 1999: 93, fig. 56c–e; Chabal et al. 2012.
91. Strabo 3.1.8.
92. Tarradell 1959.
93. Late antique villas with armchair voussoirs include Gelleneuve, Bansayrè, Gleyzia, Saint-Vincent-Couladere, and Valentine (WebCat. 7-A).
94. Balmelle 2001; Sivan 1993; Matthews 1975.
95. Sivan 1993.
96. Esmonde Cleary 2013: 245–50.
97. In Tranoy's study of Gallaecia, his distribution of villas shows that a vast majority are either third/fourth century or undated; very few can be definitively dated to the first/second century (Tranoy 1981: Carte 34).
98. Díaz and Menéndez-Bueyes 2005: 272–73.
99. Strabo 3.3.2, 3.3.8, 3.4.16.
100. *Not. Dig. Occ.* 42.25–30. Legio VII Gemina at León, Cohors III Lucensium at Lugo, and the Cohors I Celtiberorum at A Coruña.
101. Díaz and Menéndez-Bueyes 2005: 277.

102. Díaz and Menéndez-Bueyes 2005: 279–81.
103. Fernández Ochoa and Morillo 2005: 329–30. See also Richmond 1931. The walls of cities in northwest Spain were long ago seen as a coherent stylistic group characterized by the close set of protruding towers, and engineering expertise from the Legio VII is assumed to have lent a hand in their construction.
104. Díaz and Menéndez-Bueyes 2005: 279–82; Bowes 2013.
105. Bowes 2013: 215.

CHAPTER 8. VAULT BEHAVIOR AND STRUCTURAL FORM

1. Yegül 1986: 117–32. I am grateful to Fikret Yegül for discussing the structural issues during our visit to the Sardis baths during the summer of 2006. The Baths of Vedius at Ephesus have also been published in detail, but less emphasis was placed on analysis of its structural behavior: Steskal and La Torre 2008.
2. Yegül 1986: 132, figs. 213, 215, 216.
3. Amici 2011, Amici 1997; DeLaine 1990; Hoffmann 1980; Lancaster 2005a; Olivier 1983.
4. Lancaster 2005a: 128.
5. Another large vaulted portico at Dougga may have existed at the Sanctuary of Saturn/Baal, which had a 4.5 m wide portico along three sides of the rectangular enclosure. J.-C. Golvin and M. Khanoussi (2005: 146, fig. 99) have suggested that it was covered with vaulting tubes based on the presence of a groove, containing the remains of mortar, that extended the length of the back side of a horizontal entablature block found on the site. See also Poinssot 1958: 65. If so, it presumably would have been a barrel vault, which would be rare, and it would be among the widest of the vaulted porticoes recorded thus far. Unfortunately the back wall of the Sanctuary of Saturn/Baal is not preserved to provide a confirmation of the vault configuration. To evaluate this proposal one would need further information, such as the dimensions of the entablature block and the type of mortar (lime or gypsum) found in the groove.
6. Golvin and Khanoussi 2005: 145–47.
7. Given a square cross vault with a 3 m span and a flat roof and a similar sized sail vault, the sail vault has a volume that is over 50% more than that of the cross vault. A comparison of the horizontal thrusts on the abutments of these two forms could yield insight into the choices made by the builders, but this type of analysis is beyond my own expertise. For 3-D thrust analysis, see Block and Ochsendorf 2007.
8. Lancaster 2005a: 149–55, 225–29. For a more detailed explanation of how this method can be used, see Zalewski and Allen 2009. The graphic method of thrust line analysis I use here is based on the concept of "plastic theory" and limit analysis introduced in the 1960s for analyzing masonry structures by J. Heyman, best known for his 1995 book, *The Stone Skeleton: Structural Engineering of Masonry Architecture*. I am grateful to Professor Heyman for his encouragement in my early forays into thrust line analysis and to John Ochsendorf at MIT for helping me learn how to apply it.
9. For Archimedes, see Corradi 2005. For a brief overview of the development of modern structural theory, see Lancaster 2005a: 10–12, 149–52 and references therein.
10. Huerta (2004: 133–66) examines how later builders during the medieval period applied such types of rules of thumb for their vaulting with reliable results.
11. For building disasters, see Oleson 2011.
12. In the provinces, modules were sometimes based on local units of measure, but regardless of the measure, the wall thickness had to be enough to support the vaults. I use the Roman foot (about 29.6 cm) in this exercise because it was the most standardized unit.
13. The weight of the terracotta making up the hollow voussoirs is assumed to be 1,700 kg/m^3. The supporting wall is given a weight of 2,000 kg/m^3, which is appropriate for a range of materials (brick, mortar, sandstone). Heavier walling material would increase the stability, so this figure should yield conservative results. The maximum arc of embrasure was found using the applet at web.mit.edu/masonry/interactiveThrust/applets/applet03.html (last accessed June 17, 2015).
14. Rankine 1858. For further explanation, see Lancaster 2005a: 158–59.
15. Cunliffe and Davenport 1985: 7–9, 39–42.
16. Cunliffe 1969: 98–99, 118; Cunliffe and Davenport 1985: 50–53.
17. Cunliffe 1969: 130.
18. Cunliffe and Davenport 1985: 65.
19. Cunliffe and Davenport 1985: 50–53, fig. 28, pls. 10–11.
20. The pediment of the porch is preserved so its front width is known (Cunliffe and Davenport 1985: fig. 35). The height is not known, but a reasonable estimate can be made based on proportional relationships of its facade.
21. Ochsendorf 2006.
22. Cunliffe 1971: 46, 58, Cunliffe 1969: 98–99, 117–18.
23. Davis 1884; Cunliffe 1969: 98–99.
24. Benoit (1977: 62) states the dimensions of the ribs as 41 cm long and 34 cm wide, but in the drawing in pl. 11 they are shown as 34 cm tall. Bouet (1999: 93) cites the measurements given by Benoit, but in his drawing in fig. 55b, he shows them as about 38 cm tall and 41 cm wide. I have used the figure of 34 cm tall in the models because that is the dimension that matches the height of the vertical grooves containing the voussoirs.
25. This reconstruction is based on published plans, my own photographs and measurements from the site, and discussions with P. Vitti, whose reconstruction is somewhat different (Vitti 2008 (pub. 2010): fig. 9). The heights were determined by counting brick courses and using an

average of 62.5 cm per ten courses, which also corresponds to the average of 62–64 cm published by Ginouvès (1972: 233).

26. Lancaster 2009b: 385–86, fig. 19.
27. Vitti (2008 (pub. 2010): fig 32) also published a similar analysis using a different roof reconstruction and found that the thrust line exited the abutment.
28. Piérart 1974: 782; Aupert 2001: 445 n. 419, Aupert 1983: 851; Banaka-Dimaki et al. 1998: 328.
29. Mark and Çakmak 1994: 277–79. Jackson et al. (2009: 2488–90) found the average tensile resistance of bricks at Trajan's Markets was 2.4 MPa. Tensile strength tests on mortar are less common than compressive strength tests, but a general estimate is that the tensile strength of mortar and modern concrete averages around 10% of the compressive strength. See figures in Jackson et al. 2009: 2491.
30. Mark and Hutchinson 1986: 29–32.
31. Lancaster 2010.
32. Riethmüller 2005.
33. Aupert and Ginouvès 1989; Vitti 2008 (pub. 2010): 217, 247 following Aupert.

CHAPTER 9. VAULTING TECHNIQUES IN CONTEXT

1. DeLaine 1997; Wilson 2006; Russell 2013; Camporeale et al. 2008; Camporeale et al. 2010; Camporeale et al. 2012.
2. Fournet 2011: 328–35.
3. Clarke and Engelbach 1990: 187, fig. 224.
4. Yamani 2001: 396–98, figs. 7, 12, photos 13–14.
5. Martín and García Roselló 2002: 203.
6. Valencia: Marín Jordá and Ribera Lacomba 2000: 153. Labitolosa: Fincker 2009.
7. Yegül 2013: 85–86.
8. Hollow voussoirs occur in villa baths in 51% of the identifiable contexts (28/55). This figure excludes London, because the various contexts there are unknown. Armchair voussoirs occur in villa baths in 59% of identifiable contexts (35/59).
9. Alcock 1993: 62–71; Zarmakoupi 2013. Literary sources, mostly from the late Roman period, describe villas in the Greek East that had some pretensions, such as bath buildings, but few such structures have been excavated. One example known from Greece is the elaborate villa of Herodes Atticus at Eua/Loukou south of Argos in the Peloponnese, but Herodes Atticus was not typical nor was his villa (Rossiter 1989: 102–04).
10. For estate management in Asia Minor, see Corsten 2005. In Africa Proconsularis, see Kehoe 1984, Kehoe 2013.
11. Thonemann 2011: 251–58.
12. Mitchell 1993: 148–62. Village settlements often inhabited such lands, a hangover from the structure that had existed under the Hellenistic monarchs (Broughton 1938: 627–48).
13. Nevett 2008. See also Rind 2009: 66, 76, 88.
14. Cuspius Rufinus: *CIL* 15.2322. Cusinius Messalinus: *CIL* 15.957–58, S. 280. Ti. Claudius Celsus Orestianus: *CIL* 15.3.92–95.
15. Kehoe 2013.
16. de Vos 2013; Hitchner 1995b; Hitchner and Mattingly 1991.
17. Lewit (2011) has a very good discussion of the various factors influencing the rise of fine ware production in North Africa.
18. For recent overviews of deforestation in the Mediterranean, see Sallares 2007: 21–26.
19. Harris 2013.
20. One study from around Segermes in northern Tunisia found little evidence for tree pollen in the area, but this appears to have been the case even before the arrival of the Romans (Kolstrup 1994). Pollen studies produce stratigraphical data over long periods of time that provide an overview of trends, but to get absolute dates the data need to be linked to datable material such as wood or carbon from particular strata. In broad environmental studies it is not always possible to isolate or give absolute dates for the Roman strata.
21. Andrieu-Ponel et al. 2000.
22. Chabal and Laubenheimer 1994.
23. Chabal et al. 2012.
24. Mighall et al. 2006.
25. Pinto et al. 2010; van der Knaap and van Leeuwen 1995: 201; Ramil-Rego et al. 1998: fig. 4.
26. For the use of social network theory on the brick stamps of the Tiber valley, see Graham 2006.
27. Graham 2011; Setälä 1977: 34–37.
28. Vitr. *De arch.* 6.*prae*.6–7. He also notes that the bath should be near the kitchen in designing one's villa (6.6.2).
29. Brandon et al. 2014: 227–30.
30. Higginbotham 1997: 55–64 (on social status), 58 (on dates first century BCE to first century CE).
31. Varro, *Rust.* 3.17.2.
32. Varro, *Rust.* 3.17.1–9.
33. Oleson in Brandon et al. 2014: 227–30.
34. Winter 2009: 581–82.
35. Lancaster 2011; Gambin 2012: 150.
36. Williams-Thorpe 1988: 284–88; Williams-Thorpe and Thorpe 1989.
37. Lancaster et al. 2010; Spanu 2003b: 25; Verzone 1957: 57.
38. Keay (2012: 12) notes the intensity of the exchange from the late first century BCE through the second century CE. See also Ramallo Asensio and Martínez Andreu 2010.
39. Hohlfelder posited merchant captains as one potential source for the spread of concrete harbor-building technology (Brandon et al. 2014: 226).
40. MacMullen 1959; Mitchell 1987; Greene 1992.
41. Bidwell (2005: 36) explores connections between the military in Britain and Spanish origins of the recruits. One of the Spaniards he mentions came from a fort at Slack that produced the armchair voussoirs.
42. One of the inscribed letters revealed Hadrian's pledge of 65,000 denari in 125 CE to remedy the flood problem, an

amount that had been determined by his specialist (ἐπιστή-μονες, *epistimones*). The specialist is not explicitly cited as someone in the military, but in another fragmentary letter from the same archive, soldiers (στρατιώταις, *stratotais*) are mentioned as part of his entourage (Fossey 1982: no. 3, no. 7).

43. Oleson in Brandon et al. 2014: 230–33.
44. Haselberger 1997.
45. Vitr. *De arch.* 10. 7.4; 10.13.8.
46. Downey 1948: 113. For further discussion of Heron and vaulting, see Lancaster 2005a: 10–12.
47. Lucore 2013. For Archimedes, see also in the same volume Napolitani and Saito 2013.
48. *SHA* Hadrian 13. 5: "Hardly any emperor ever traveled with such speed over so much territory."; 19.2: "In almost every city he built some building and gave public games." (Trans. D. Magie, Loeb 1921).
49. Dio 69.5.3 (Trans. E. Cary, Loeb 1925).
50. Aur. Vict. *Caes.* 14.5 (Trans. Boatwright 2000: 22 n. 22).
51. Schorndorfer 1997: 19, 45–46, 57, 78, 118. M. T. Boatwright (2000: 204–09) counted 130 cities throughout the empire that received more than 210 interventions, including donations of buildings, money, and grain; tax remittances; status upgrades; and games and festivals.
52. Both buildings are identified as *horrea* in their inscriptions (*CIL* 3.232 (Myra), 3.12129 (Patara). Interestingly, the companion *horrea* at Myra, which bore a Latin inscription identical to the one at Patara, were covered by a timber roof.
53. See Chapter 3, note 66.
54. *IvE* 2.274.
55. Lactant., *De mort. pers.* 8.8–10 (Trans. Jones 1964: 66).
56. Bowes 2010: 90–91.
57. Esmonde Cleary 2013: 116.
58. Esmonde Cleary 2013: 249–56.

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A note on the terminology: I use "brick" to refer to flat building units for walls and vaults, whereas I use "tile" to refer to items that have more complex forms, such as roof tiles and box-tiles (the distinction is not appropriate for all contexts, e.g. a "tile maker" can also make bricks). For place names, I have used the name that is most common, regardless of whether it is modern or ancient, but some cross references to alternative designations are provided. The monuments and places in the Web Catalogs and the Web Figures are not included in this index. Numbers in bold indicate pages with illustrations.