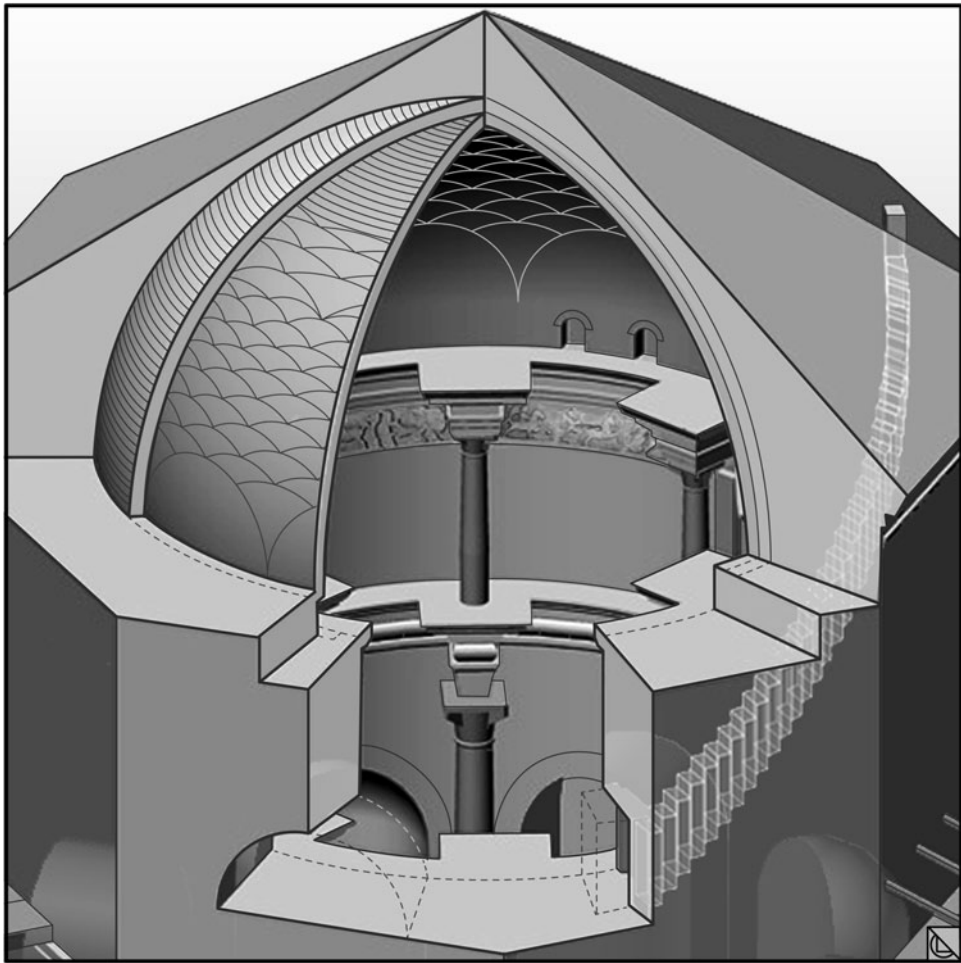


INNOVATIVE VAULTING IN  
THE ARCHITECTURE OF THE ROMAN EMPIRE

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).

INNOVATIVE VAULTING IN  
THE ARCHITECTURE OF  
THE ROMAN EMPIRE

1<sup>st</sup> to 4<sup>th</sup> Centuries CE

LYNNE C. LANCASTER  
Ohio University



CAMBRIDGE  
UNIVERSITY PRESS

32 Avenue of the Americas, New York, NY 10013-2473, USA

Cambridge University Press is part of the University of Cambridge.  
It furthers the University’s mission by disseminating knowledge in the pursuit of  
education, learning, and research at the highest international levels of excellence.

[www.cambridge.org](http://www.cambridge.org)  
Information on this title: [www.cambridge.org/9781107059351](http://www.cambridge.org/9781107059351)  
© Lynne C. Lancaster 2015

This publication is in copyright. Subject to statutory exception  
and to the provisions of relevant collective licensing agreements,  
no reproduction of any part may take place without the written  
permission of Cambridge University Press.

First published 2015

Printed in the United States of America

*A catalog record for this publication is available from the British Library.*

*Library of Congress Cataloging in Publication Data*  
Lancaster, Lynne C., 1964–

Innovative vaulting in the architecture of the Roman Empire : 1st to 4th centuries CE /  
Lynne C. Lancaster, Ohio University.

pages cm

Includes bibliographical references and index.

ISBN 978-1-107-05935-1 (hardback) – ISBN 978-1-107-69135-3 (paperback)

1. Vaults (Architecture) – Rome. 2. Building, Terra-cotta – Rome. 3. Architecture, Roman.  
4. Architecture and society – Rome. I. Title.

TH2160.L36 2015

721'.430937–dc23 2015021258

ISBN 978-1-107-05935-1 Hardback

Cambridge University Press has no responsibility for the persistence or accuracy of  
URLs for external or third-party Internet Web sites referred to in this publication  
and does not guarantee that any content on such Web sites is, or will remain,  
accurate or appropriate.

Cambridge University Press  
978-1-107-05935-1 - Innovative Vaulting in the Architecture of the Roman Empire: 1st to 4th Centuries CE  
Lynne C. Lancaster  
Frontmatter  
[More information](#)

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

Cambridge University Press  
978-1-107-05935-1 - Innovative Vaulting in the Architecture of the Roman Empire: 1st to 4th Centuries CE  
Lynne C. Lancaster  
Frontmatter  
[More information](#)

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)

Cambridge University Press  
978-1-107-05935-1 - Innovative Vaulting in the Architecture of the Roman Empire: 1st to 4th Centuries CE  
Lynne C. Lancaster  
Frontmatter  
[More information](#)



CONTENTS

<i>List of Figures</i>	<i>page</i> xiii
<i>List of Tables</i>	xviii
<i>List of Web Figures</i>	xix
<i>List of Web Catalogs</i>	xxi
<i>Preface</i>	xxiii
1 INTRODUCTION	I
How to Use This Book	I
Goals and Intentions	2
Method and Approach	4
Provincial Administration and the Building Industry	7
Building Vaults: Structure and Construction	12
Structural Behavior, 12 • Material Properties, 14 • Centering, 15	
Final Thoughts	17
2 OPUS CAEMENTICIUM	19
Terminology	20
What Is Pozzolana?	21
How to Recognize Volcanic Ash	24
How Do Pozzolans Work?	24
Survey of Reactive Additives for Mortar	26
Caementa: Sources of Stones and Structural Strategies	29
Conclusions	36
3 BARREL VAULTS OF BRICK	39
Methods of Construction: Terminology	40

CONTENTS

Radial Brick: Early Graeco-Roman Examples	42
Radial Brick: Purpose	45
Pitched Mud Brick: Pre-Roman Developments	49
Vertical Brick: Early Examples	50
Vertical Brick: Diffusion	57
Vertical Brick: Purpose	58
Technology Transfer and the Near East	64
Conclusions	66
4 COMPLEX VAULT FORMS OF BRICK	70
Vault Types: Terminology	70
Complex Vault Forms: Pre-Roman Developments	72
Mud Brick Sail Vaults in Early Roman Egypt	73
Fired Brick Sail Vaults Outside Roman Egypt	79
Pitched Brick Domes and Semidomes	88
Conclusions	94
5 VAULTING TUBES	99
Early Development of Vaulting Tubes	100
Introduction of Vaulting Tubes with Nozzles	106
Role of the Military in the Diffusion Outside North Africa	108
The North African Economy	112
An Export Commodity?	115
Purpose of the Nozzle Tubes	115
Effects on Architectural Space	118
A New Vault Form Is Born	122
Advent of Lightweight Shell Vaults	126
Conclusions	126
6 HOLLOW VOUSOIRS	129
Analytical Tools for Studying Hollow Voussoirs	129
Early Examples	132
The Next Generation	138
Purpose	140
Production Modes and Diffusion	145
Conclusions	149
7 VAULTING RIBS OF ARMCHAIR VOUSOIRS	152
Precursors: Flanged Terracotta Bars	153
Early Terracotta Armchair Voussoirs	156

CONTENTS

Stone Armchair Voussoirs	158
Purpose of Armchair Voussoir Ribbing	161
Heated Vaults?	163
Production Modes and Diffusion	169
Conclusions	172
8 VAULT BEHAVIOR AND STRUCTURAL FORM	177
Vaults as Part of Structural Systems	177
Thrust Line Analysis as a Tool for Evaluating Structural Behavior	180
Case Study 1: Hollow Voussoirs vs. Solid Brick – A Comparison of Structural Efficacy	182
Case Study 2: The Sanctuary of Sulis Minerva at Bath	184
Case Study 3: The North Baths at Cimiez	187
Case Study 4: The Cult Complex at Argos	189
Structural Analysis as an Aid to Cultural Understanding	191
9 VAULTING TECHNIQUES IN CONTEXT	192
The Role of Bath Building in Technology Transfer	193
The Building Industry, Terracotta Production, and Agricultural Export	195
Deforestation as a Factor in Construction Innovation?	197
Networks and Technology Transfer	199
Chronological Patterns	202
Notes	205
Works Cited	223
Index	247

Cambridge University Press  
978-1-107-05935-1 - Innovative Vaulting in the Architecture of the Roman Empire: 1st to 4th Centuries CE  
Lynne C. Lancaster  
Frontmatter  
[More information](#)

LIST OF FIGURES

All drawings and photographs are by the author unless otherwise noted.

<i>Frontispiece</i> . Drawing of the dome of the Mausoleum of Diocletian at Split (detail of Figure 60).	page ii
1. Illustrations of the six techniques under examination.	2
2. Photo of column dedication at the Temple of Aphrodite at Aphrodisias (photo: P. Stinson).	3
3. Photo of base of the Obelisk of Theodosius I, Istanbul.	10
4. Drawing of arch showing terms used in text.	12
5. Drawings showing dome built of radial voussoirs and stress patterns in an uncracked hemispherical dome.	13
6. Photo of a substructure chamber of the Temple of Trajan at Pergamum.	16
7. Author's sketch of the process of centering removal proposed by K. Nohlen for the Temple of Trajan at Pergamum.	17
8. Drawing of <i>opus caementicium</i> vault.	19
9. Maps showing extent of the use of various types of mortar and <i>caementa</i> .	23
10. Photos of lightweight volcanic stones in vaults from the Antonine Baths at Carthage and the East Baths at Leptiminus.	31
11. Map showing locations of volcanic systems and navigational routes around Sicily.	32
12. Photos of lightweight calcareous tufa in vaults at the bath at Newport on the Isle of Wight, Diocletian's Palace at Split, and the Agora Baths at Elaeussa Sebaste.	33
13. Photos of examples of radially laid <i>caementa</i> combined with courses of radially laid brick at the Palace of Diocletian at Split and the Imperial Thermae at Trier.	34
14. Photos of examples of long narrow <i>caementa</i> laid radially at the amphitheater at Salona, Croatia, and the Temple of Asclepius at Pergamum.	35
15. Photos of examples of small irregular <i>caementa</i> laid radially at the Baths of Julia Memmia at Bulla Regia and the bath at Antiochia in Pisidia.	35

LIST OF FIGURES

16. Photo of fallen vault from Casa de la Esedra at Italica.	36
17. Drawing showing methods of laying brick for barrel vaults.	40
18. Distribution maps of brick barrel vaults.	41
19. Photo of remains of vertical brick vault in a cistern at Rhodiapolis.	42
20. Photo of remains of brick vault at the Hadrianic <i>Horrea</i> at Patara.	44
21. Plan of Ephesus showing location of monuments mentioned in the text.	45
22. Methods of vault construction at the Baths of Faustina at Miletus.	47
23. Photos of centering holes in radial brick vaults at the East Baths at Ephesus, the Uç Goz Baths at Tralles, and the Brick Baths at Myra.	48
24. Photo of a Roman pitched mud brick vault from a house at Soknopaiou Nesos in the Fayum, Egypt (photo: S. Camporeale), with diagram of Hooke’s hanging chain.	50
25. Chart of vault forms and sizes in Egypt and the Levant/Near East.	51
26. Ziller’s drawings of Aqueduct of Hadrian at Athens (Ziller 1877: Taf. 8).	52
27. Map of Athens in the second century CE.	53
28. Plan of Roman Eleusis.	54
29. Plan of Argos, Greece.	55
30. Photo of second-century drain in the agora at Argos (© École française d’Athènes).	55
31. Author’s reconstruction of main room A1 of cult complex (Theater Baths) at Argos.	56
32. Photo of the vault of main room A1 of cult complex (Theater Baths) at Argos.	57
33. Photo showing detail of vertical bricks in main room A1 of cult complex (Theater Baths) at Argos.	57
34. Photos of vaults combining radial and vertical bricks at Terrace House 2 at Ephesus, the basilica at Aspendus, the Baths of Vespasian at Patara, and the Southwest Baths at Patara.	59
35. Photos of centering holes used with vertical brick at the Theater Baths at Argos and the odeum at Thessaloniki.	60
36. Photo of Outer Baths at Hierapolis, Turkey, with diagram of spreading arch.	61
37. Photo of the substructure vaults of the agora basilica at Izmir.	62
38. Photos of barrel vaults with spines of different materials at the crown at Terrace 2 at Ephesus, the “Love House” at Ephesus, the Small Baths at Aspendus, and the cryptoporticus at the forum at Coimbra, Portugal (photo: M. Shadis).	63
39. Photos of barrel vaults with sections of vertical brick at the Arch of Galerius at Thessaloniki and St. John’s Basilica at Ephesus.	64
40. Map showing locations of pre-Roman brick vaults.	66
41. Reconstruction drawing of a pitched brick sail vault before the completion of its crown.	70
42. Distribution map of pitched brick vaults with complex forms and of sail vaults.	71
43. Drawings of vault forms discussed in Chapter 4.	72

LIST OF FIGURES

44. Mud brick vault types found in the Fayum during the Roman period.	74
45. Photo of sail vault in house II.201 at Soknopaiou Nesos (photo: S. Camporeale) with the excavator's site sketch of the same vault.	75
46. Photo of an arched barrel vault in house I.108 room M at Soknopaiou Nesos (photo: Kelsey Museum).	77
47. Author's drawing of vaults at the North Bath at Karanis, Egypt.	78
48. Photo of sail vault built using the fan method at Terrace House 1 at Ephesus.	79
49. Plan of Terrace Houses at Ephesus.	80
50. Author's reconstruction of the vaulted atrium in the Domus of Terrace House 1 at Ephesus.	81
51. Photo of bath in peristyle of Residential Unit 6 in Terrace House 2 at Ephesus.	82
52. Plan and photo of the West Mausoleum at Side.	84
53. Author's reconstruction of the structural scheme of the portico of the West Mausoleum at Side.	85
54. Photo of brick sail vault at the East Tomb at Side.	86
55. Photo of brick sail vaults at the Small Baths at Aspendus.	87
56. Photo of brick sail vault at Northeast Baths in Sanctuary of Asclepius at Epidaurus.	88
57. Photo of exterior niche of the Rotunda of Galerius at Thessaloniki (early fourth century CE).	89
58. Photo of niche at the Palace of Galerius at Thessaloniki (early fourth century CE).	89
59. Photo of sail vault from one of the towers of the fortification walls of the Palace of Galerius at Felix Romuliana (modern Gamzigrad, Serbia) (early fourth century CE) (photo: U. Wulf-Rheidt).	89
60. Author's reconstruction of the Mausoleum of Diocletian at Split.	90
61. Photo of the fan construction of the dome at the Mausoleum of Diocletian at Split.	91
62. Drawing of geometry and layout of dome at the Mausoleum of Diocletian at Split.	91
63. Photo of the dome of the Mausoleum of the Diocletian at Split (photo: G. Nikšić).	93
64. Photos of decorative use of pitched brick at St. Demetrius at Thessaloniki and the sail vaults next to the theater at Nysa.	95
65. Drawing of a barrel vault made of terracotta vaulting tubes.	100
66. Distribution map of vaulting tubes and vaulting pots used for kiln roofs.	101
67. Photo of fallen vaulting tubes at the North Baths at Morgantina (photo: S. Lucore).	102
68. Chart showing the development of vaulting tubes and pots.	103
69. Author's reconstruction of the system of vaulting at the bath at Cabrera de Mar.	104
70. Author's reconstruction of a generic loaded kiln employing vaulting pots for the roof.	106

LIST OF FIGURES

71. Use of water-pipe type tubes at the House of Fabius Rufus at Pompeii and the cistern of the Nymphaeum of the Chalcidium at Leptis Magna.	106
72. Photo of <i>fabrica</i> at Chemtou.	108
73. Plan of bath at Aquae Flaviae.	109
74. Plans of baths at Chester and at Thelepte.	110
75. Plan of Bath F3 at Dura-Europus with photo of fallen tube vault from portico (photo: Yale University Art Gallery).	111
76. Map of Africa Proconsularis with distribution of vaulting tubes.	113
77. Photo of remains of tube vaults at the House of Dionysus and Ulysses at Dougga.	117
78. Photos of the “Licinian” Baths at Dougga. Vault with impressions of reed mat along intrados and vault with remains of vaulting tubes along intrados (photo: M. Lewis).	119
79. Plan showing types of centering used at the Baths of Julia Memmia at Bulla Regia.	120
80. Plan and photo of House of Amphitrite at Bulla Regia.	121
81. Plan and photo of House of the Hunt at Bulla Regia.	122
82. Plan and photo of remains of the Sanctuary of Juno Caelestis at Dougga.	123
83. Diagrams of geometry of the squinch vault, the half sail vault, and the composite sail vault.	124
84. Drawing and photo of remains of the half sail vault at the Baths of the Cyclops at Dougga.	125
85. Drawing showing the geometry and tube configuration at Kobbat Bent el Rey at Carthage.	125
86. Drawing of vault made of hollow voussoirs.	130
87. Distribution map of hollow voussoirs.	131
88. Drawings of hollow voussoir roller dies mentioned in the text (Betts et al. 1994).	132
89. Reconstruction of a <i>caldarium</i> with <i>tegulae mammatae</i> on both walls and vaults.	133
90. Photos of a Westhampnett voussoir and a double flue box-tile from the bath at Angmering.	134
91. Distribution map of London-Sussex die group.	135
92. Plan of bath at Angmering (courtesy Littlehampton Museum).	136
93. Excavation photograph of bath at Angmering (photo: Littlehampton Museum).	137
94. Author’s reconstruction of the <i>caldarium</i> of the bath at Angmering.	138
95. Photos of Westhampnett hollow voussoir and the similar type from Bath.	139
96. Photos of chunks of hollow voussoir vaulting from the Sanctuary of Sulis Minerva at Bath.	141
97. Chart of vault spans calculated from extant hollow voussoirs.	142
98. Author’s reconstruction of the Sacred Spring of the Sanctuary of Sulis Minerva at Bath.	144
99. Distribution maps of roller stamps.	146
100. Drawings of graffiti on Westhampnett voussoirs.	149



LIST OF FIGURES

101. Drawing of armchair voussoir ribbed vault using double slabs.	153
102. Distribution map of armchair voussoirs.	154
103. Author’s reconstruction of vault made of terracotta bars with details of bars found at the Republican baths at Fregellae, Italy (third to second century BCE) and of a bar from Massa kiln site (late second to mid-first century BCE).	155
104. Drawings of early examples of armchair voussoirs.	156
105. Bath at Baetulo (first century BCE to first century CE). Reconstruction of vault (c. 6 m) made with H-type voussoir supporting tile slabs.	157
106. Photos of odeum at Gortyn, Crete with stone armchair voussoirs supporting cavea and of crypt of the Temple of Apollo at Claros (photo: W. Aylward).	159
107. Photo of barrel-vaulted roof of stone armchair voussoirs at the “Temple of Diana” at Nîmes.	160
108. Author’s reconstruction of the hanging tile ceiling at Séviac villa baths at Montréal.	162
109. Photo of <i>tepidarium</i> of the North Baths at Cimiez.	164
110. Author’s reconstruction drawings of different types of wall heating systems used with armchair voussoirs in Iberia and Morocco.	165
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.	166
112. Plan of East and West Baths at Mirobriga, showing where armchair voussoirs were found with a photo of the wall heating system (photo: J. Biers).	168
113. Distribution map of villa baths employing armchair voussoirs.	175
114. Diagram of compressive forces flowing through the structure of the Gymnasium Baths at Sardis.	178
115. Diagram showing the pattern of lateral forces in a portico with cross vaults and a portico with sail vaults.	179
116. Drawing of a funicular polygon diagram used in graphic thrust line analysis.	181
117. Drawing showing the parameters for the models to compare the structural effect of different sized vaults employing hollow voussoirs.	183
118. Thrust line analysis of the hollow voussoir vault of the Sacred Spring at the Sanctuary of Sulis Minerva at Bath.	185
119. Thrust line analysis of the hollow voussoir vault of the Great Bath at the Sanctuary of Sulis Minerva at Bath.	186
120. Thrust line analysis of the <i>frigidarium</i> vault of the North Baths at Cimiez.	188
121. Thrust line analysis of the main room A1 of the cult complex (Theater Baths) at Argos.	190

LIST OF TABLES

1. Composition (%) of various organic ashes	<i>page</i> 26
2. Complex vault forms at Karanis	76

LIST OF WEB FIGURES

The web figures are downloadable as color PDF files from  
[www.cambridge.org/vaulting](http://www.cambridge.org/vaulting).

- 1. Photo of Didyma oracle inscription at the theater at Miletus.
- 2. Photos of volcanic ash from the Colli Albani deposits at Rome and the Monte Procida deposits on the Bay of Naples.
- 3. Photo of vaults with volcanic scoria in Cilicia at baths at Anazarbus and Tarsus.
- 4. Photo from the Antonine Baths at Carthage of a fallen piece of vaulting containing volcanic scoria.
- 5. Photo from the East Baths at Leptiminus of a fallen piece of vaulting containing volcanic pumice.
- 6. Photos of examples of radially laid *caementa* combined with courses of radially laid brick at the Palace of Diocletian at Split and the Imperial Thermae at Trier.
- 7. Photo of remains of a brick vault at the Hadrianic *Horrea* at Patara.
- 8. Methods of vault construction at the Baths of Faustina at Miletus.
- 9. Photo of the remains of the *caldarium* vault at the East Baths at Ephesus.
- 10. Photo of the remains of the *caldarium* vault at the Uç Goz Baths at Tralles.
- 11. Photo of the remains of the vertical bricks at the Baths of Vespasian at Patara.
- 12. Photo of the remains of the vertical bricks at the Southwest Baths at Patara.
- 13. Photo of the impressions of the vertical bricks in a vault at Baths III.2.b at Anamurium.
- 14. Photo of the remains of vertical brick vaulting at the Agora Baths at Side.
- 15. Photo of the cut stone, arched substructures of the basilica in the agora at Izmir.

LIST OF WEB FIGURES

- 16. Photo of the cistern vault under the agora at Cremna.
- 17. Photo of the atrium of the Domus in Terrace House 1 at Ephesus.
- 18. Photo of the brick sail vaults in the peristyle bath of RU6 in Terrace House 2 at Ephesus.
- 19. Photos of brick sail vaults at the Small Baths at Aspendus.
- 20. Photo of the Leonidaion Baths at Olympia showing a radial brick cross vault with a vertical tube at the crown (photo: Evan Scherer).
- 21. Photo of the remains of a pitched brick sail vault at the Northeast Baths in the Sanctuary of Asclepius at Epidaurus.
- 22. Photo of a radial brick dome in the substructures of the Palace of Diocletian at Split.
- 23. Photo of the decorative brickwork in the semidomes of the niches in the East Tomb at Side.
- 24. Photo of the radially-laid *caementa* over a tube vault at the Baths of Julia Memmia at Bulla Regia.
- 25. Photo of remains of tube vaults at the House of Dionysus and Ulysses at Dougga.
- 26. Photos of substructure galleries of the “Licinian” Baths at Dougga.
- 27. Photo of composite sail vault at the House of Ducks and Seasons at Dougga.
- 28. Photo of fallen piece of hollow voussoir vaulting from the Baths of Sulis Minerva at Bath.
- 29. Photo of fallen piece of hollow voussoir vaulting from the Baths of Sulis Minerva at Bath.
- 30. Photo of fallen piece of hollow voussoir vaulting from the Baths of Sulis Minerva at Bath.
- 31. Photo of *tepidarium* of the North Baths at Cimiez (Nice).
- 32. Photo of a lintel arch with joggle joints at the theater at Orange.
- 33. Plan of the baths at the Sanctuary of Sulis Minerva at Bath.

LIST OF WEB CATALOGS

The web catalogs are downloadable as searchable Excel files from [www.cambridge.org/vaulting](http://www.cambridge.org/vaulting).

- 1. Large Vaults.
- 2. Mortar and *Caementa*. A: Mortar with Volcanic Ash. B: Mortar with Crushed Terracotta. C: Mortar with Organic Ash. D: Mortar with Hydraulic Lime. E: Lightweight *Caementa*.
- 3. Brick Barrel Vaults. A: Radial Brick Barrel Vaults. B: Vertical Brick Barrel Vaults.
- 4. Complex Vault Forms. A: Complex Vault Forms of Radial Brick. B: Complex Vault Forms of Pitched Brick. C: Sail Vaults (Any Material).
- 5. Vaulting Tubes and Pots. A: Vaulting Tubes (Land Finds). B: Vaulting Tubes (Under Water Finds). C: Kiln Vaulting Pots.
- 6. Hollow Voussoir Vaults. A: Hollow Voussoirs. B: Spans Calculated from Hollow Voussoirs. C: Spans Calculated from Building Remains.
- 7. Armchair Voussoirs and Associated Brick Types. A: Armchair Voussoirs. B: Tongue and Groove Wall Bricks. C: Walls with Strut Bricks.

Cambridge University Press  
978-1-107-05935-1 - Innovative Vaulting in the Architecture of the Roman Empire: 1st to 4th Centuries CE  
Lynne C. Lancaster  
Frontmatter  
[More information](#)

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,

## PREFACE

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



## PREFACE

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

PREFACE

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.