The Levanzo I Wreck and the Transfer of Technology by Sea in the Late Roman Mediterranean

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Introduction

As part of the Egadi Islands Survey Project (EISP), the Ufficio di Soprintendenza del Mare in Sicily and RPM Nautical Foundation (RPMNF) have surveyed the waters around the Egadi islands off the northwest Sicilian coast each summer since 2005.[1] The Roman-era Levanzo 1 wreck was discovered in deep waters carrying a consignment of vaulting tubes in association with a shipment of foodstuffs from Tunisia. The Levanzo 1 wreck has been mapped, partially excavated, and studied, with a preliminary assessment published by project codirectors Sebastiano Tusa, Soprintendente del Mare, and the author, the director of RPMNF.[2] This wreck site clearly demonstrates that vaulting tubes were shipped as cargo and allows a reinterpretation of vaulting tubes found on other wrecks. The wreck site data, combined with the evidence from their employment in structures, can be understood through a model whereby economic structures governing overseas trade during the Imperial period were a significant mechanism in the diffusion of this technology. Additionally, the distribution of vaulting tubes, both in structures and shipments, constitutes a local economic indicator.

Levanzo I Wreck

The foodstuffs shipped in amphoras on the Levanzo 1 wreck included oil, fish products, wine, and grain, along with a smaller amount of foodstuffs shipped in amphoras from Spain and the Eastern Mediterranean, coarse tableware, glass, possibly metal ingots, and over 150 individual vaulting tubes.[3] The southeastern end of the wreck site contains numerous amphoras, concretions, and a distinctly square-shaped deposit comprised of large amphora sherds, tableware, and a concentration of over 150 individual vaulting tubes (fig. 11.1).[4] Other vaulting tubes are scattered around the site, and others were collected by octopuses within some of the larger amphoras. As the small vaulting tubes are more easily buried and carried away by octopuses, the original cargo may have included upwards of 400 to 500 tubes. The vaulting tubes from the Levanzo 1 wreck are consistent in dimension, shape, and form with many of those found in situ within early Imperial architectural remains at North African sites.[5] The quantity and concentrated deposit of vaulting tubes on this site indicates that they were construction cargo and not used on board the vessel.

Many of the amphoras on the surface of the wreck were damaged and in fragmentary condition but clearly belong to large, cylindrical types. Fourteen amphoras were raised for analysis. A preliminary discussion of individual amphora dimensions, characteristics, and types was published in 2011,[6] while subsequent analysis after conservation has resulted in a

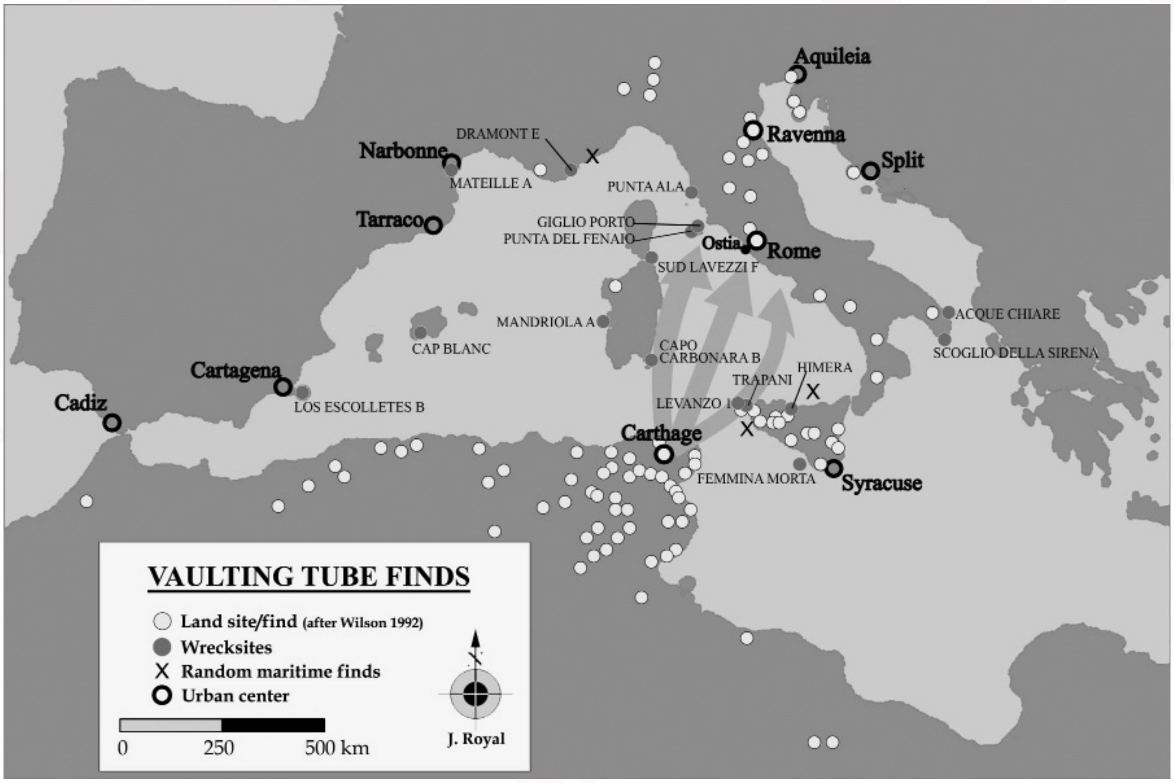

Figure 11.1. The Levanzo 1 wreck site and deposit of vaulting tubes (courtesy J. Royal).

reassessment of several amphora type identifications and a consequent shift in the ship's proposed operational date. Ceramic samples have been submitted for petrographic analyses and will be presented in a forthcoming publication along with a complete discussion of the new type identifications.[7] A summary of the new identifications is provided here, as it is pertinent to the date and origin of the cargo.

Two amphoras (SI06AA-0014 and -0017) were identified as Almagro 51C with the caveat that they did not have toes; the presence of an Almagro 51C jar on the wreck site also provided a context. Subsequently Bonifay identified another Spanish amphora, Dressel 23-Tejarillo 1.[8] The amphora identified as an Almagro 51C (SI06AA-0037) remains as such; Bonifay offered another possible identification as his type 62 produced in Nabeul, which is a good match.[9] However, nearly identical comparisons with Almagro 51C examples come from Ampurias[10] and the Chretienne D[11] and Port Vendre 1[12] wrecks. In discussions with Bonifay, he acknowledges that the two possible types have nearly identical morphology, are contemporaneous, and cannot be distinguished on form alone but require petrographic analysis. A sample from this amphora has been taken, and the results will appear in a forthcoming publication.

The most critical typology reassessment regards the most problematic amphora (SI06AA-0023), which was presented as type Keay 52. A recent consultation with Carmela Franco resulted in a reassessment of this amphora as type Ostia I, 455 in light of her dissertation on this type.[13] Although concurrent consultations with other specialists favor a Keay 52 identification, the author has opted for the identification as type Ostia I, 455. This classification alleviates the original dating conundrum, whereby the single Keay 52 jar forced the

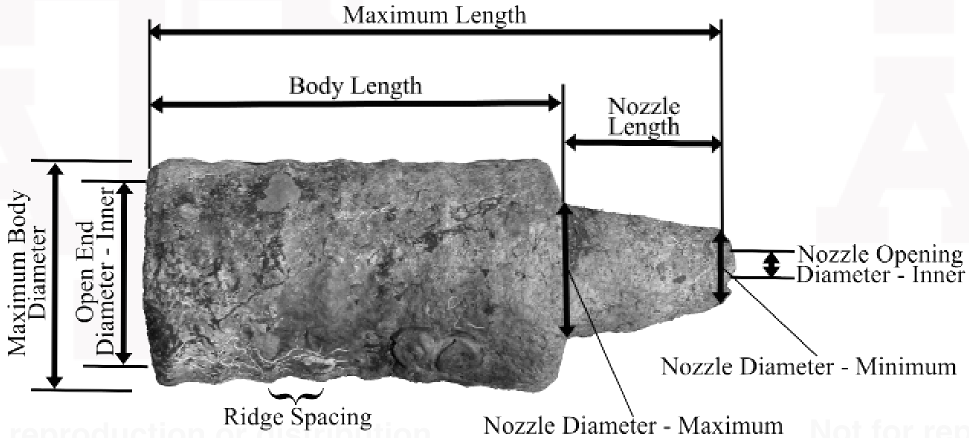

Figure 11.2. Measurements for vaulting tubes (courtesy J. Royal).

date of the wreck into the fourth century and resulted in the original estimate of 350–75 as an operational date. Additionally, results recently published by Bonifay from excavations in Tunisia provide a reassessment for the dating of type MRA1 amphoras.[14] The rim forms on the three examples raised from the Levanzo 1 wreck correspond with those in contexts dated to the last quarter of the third century. With the reclassification of the Ostia I, 455 amphora, it is now possible to refine the operational date for the Levanzo 1 wreck site to the last quarter of the third century.

Vaulting Tubes

Vaulting tubes (fig. 11.2) were ceramic building materials used almost exclusively for the construction of vaults and arches. These hollow tubes were designed such that the tapering nozzle of one nested into the open end of another to form a chain. As the nozzles were tapered and smaller than their open ends, they could be joined at a range of angles. Chains of vaulting tubes were erected side by side to form a vault. Based on in situ finds within architecture, the linked tubes were oriented such that their open ends were pointed downward and the nozzles toward the vault's apex. At the apex, a tube without a nozzle fit between two conjoining nozzles of opposing chains. They were first assembled without mortar to achieve the proper shape and then taken down and presumably stored in an organized fashion that may have included marking and record taking in order to reconstruct correctly. Once mortared in place, the form was covered with a gypsum-based plaster to produce a flat surface on each side. Concrete was poured atop the form, and the interior was covered with another plaster coating, usually a lime-based one that was decorated, leaving the tubes encased within the structure.[15] Hence the structural form of vaulting tubes was designed to hold the weight of the cement until it cured, while the cement formed the actual load-bearing structure. Alexandre Lézine noted in many structures that a few tubes had come loose due to the poor adherence of the gypsum-concrete interface, yet there was no compromise to the structure.[16]

Origin and Development

The overwhelming majority of sites where vaulting tubes were employed are located in North Africa, Sicily, and Italy. Lézine documented the use of vaulting tubes in structures spanning the second to seventh centuries from Ravenna, Italy, and Bulla-Regia, Tunisia, and produced examples of their use in third-century structures at Tabarka, Tunisia, and Tipasa, Algeria.[17] Lézine noted that the use of vaulting tubes in North Africa in the first to second centuries preceded their use in mainland Italy and surmised that they first appeared on the peninsula in the fourth century.[18] Arslan indicated an initial use in North Africa during the Imperial era after examining a number of sites in Tunisia, Sicily, and Italy[19]; likewise, Rakob postulated that vaulting tubes originated in North Africa during the second century.[20]

A comprehensive overview of vaulting tubes from terrestrial sites presented by Wilson provides a valuable catalog of vaulting tube locations that includes terrestrial and shipwreck sites, as well as museum specimens.[21] For the Roman era, Wilson observes that the overwhelming majority of sites incorporating vaulting tubes are found in Tunisia and eastern Algeria. Sicily and central Italy have the next highest occurrences, albeit somewhat later in date, while the northern section of the eastern Adriatic (Dalmatia) along with the southern and northern Italian peninsula have a few instances. Outside of these areas, the use of vaulting tubes is rare. Although Wilson does not explicitly deal with this relative chronological difference between areas, he implicitly assigns their emergence in the second century to North Africa. The distribution of vaulting tubes in Sicily shows they were not prevalent until after the third century and not widespread throughout the island until the seventh century.[22]

Although little petrology has been performed to date, fabrics suggest that most vaulting tube finds were manufactured in North Africa. Vaulting tubes from Carthage examined by Peacock had a red, orange-red, or buff fabric with a white surface due to the effect of salt and/or seawater on the lime in the clay (10YR 6/6, 7/4 or 2.5YR 5/6). All were of a local fabric, and a vaulting tube waster was found in seventh-century layer.[23] Likewise, the North-African examples from the Scoglia della Sirena wreck were of similar red fabric color (7.5YR 5/6–8),[24] and those from the Levanzo 1 wreck are fashioned from reddish clay (break, wet: 10R 3/3–4/3; surface, wet: 10R 4/4) with coarse, white inclusions.[25] Vaulting tubes found at Leptiminus, Tunisia were also considered to be of local manufacture based on their fabrics, although there is no firm date for their contexts.[26] On the basis of fabrics, Bound concluded that the vaulting tubes from the Punta del Fenaio wreck site, like others he had observed in other areas around Sicily and on other shipwrecks, were probably of North African origin.[27]

A distribution map of terrestrial and maritime find spots of vaulting tubes (fig. 11.3) and a chronological chart (fig. 11.4) of their use in architectural remains give rise to several important patterns.[28] Based on these better-dated sites, the use of vaulting tubes took place between the second and seventh centuries. The largest total number of sites is clearly in North Africa, specifically in Tunisia, and the chronological distribution shows a pattern of use where the technology is well established in North Africa by the second century and there is a peak in the use of this technology during the third and fourth centuries (fig. 11.4). The employment of vaulting tubes in construction rises in Sicily, Italy and Dalmatia by the fourth century. For the 87 known building types in which vaulting tubes were utilized, baths, churches, and residential buildings dominate in relatively equal numbers (table 11.1); however, earlier structures were primarily bath complexes and dwellings, while those from the fourth century onwards were often ecclesiastical in nature. This differentiation reflects the changing types of monumental architecture over the course of the Late Roman Empire.

Taken together, the fabric and site distribution data indicate that vaulting tubes were first used regularly in North Africa, probably sometime in the first century. Hypotheses regarding the invention of vaulting tubes in North Africa center on several ideas: (a) the reduction of

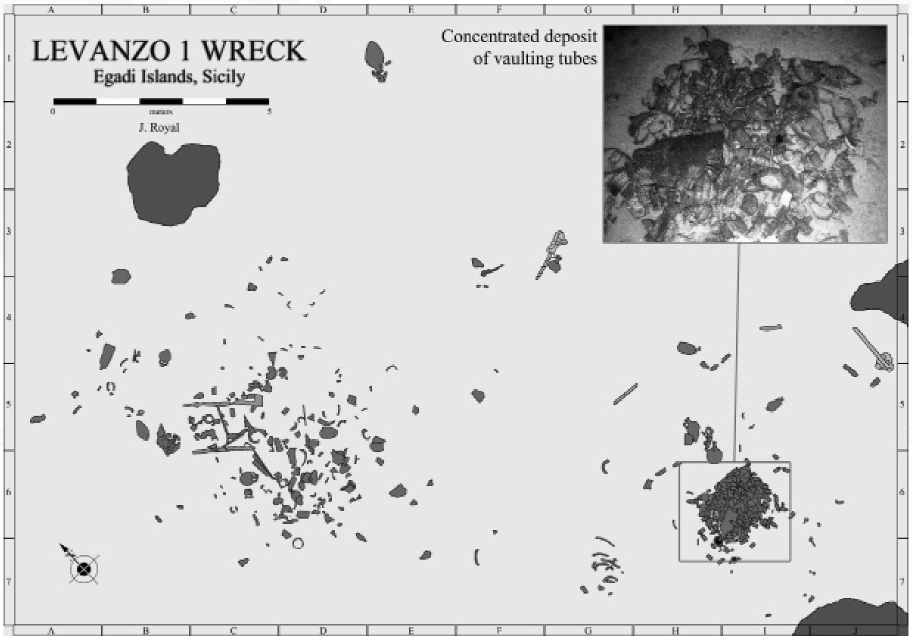

Figure 11.3. Location of vaulting tubes at terrestrial and maritime sites (courtesy J. Royal, with terrestrial sites after Wilson 1992).

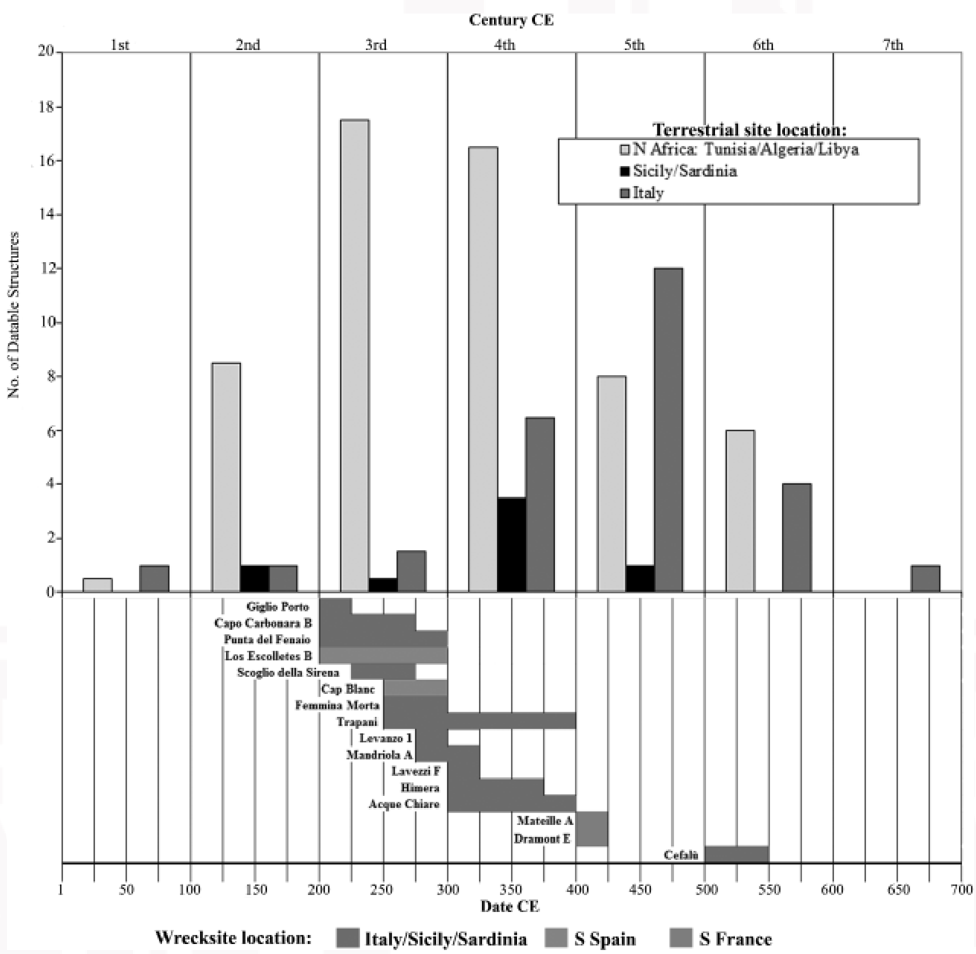

Figure 11.4. Vaulting tubes at terrestrial and maritime sites, by century (courtesy J. Royal).

Table 11.1. Vaulting tube use in regions and structures by century

	1st	2nd	3rd	4th	5th	6th	7th	Total	Total
Region									
N. Africa: Tunisia/Algeria/Libya	0.5	8.5	17.5	16.5	8	6	0	57	63.3%
Sicily Sardinia	0	1	0.5	3.5	1	0	0	6	6.7%
Italy	1	1	1.5	6.5	12	4	1	27	30.0%
Total	1.5	10.5	19.5	26.5	21	10	1	90	100.0%
Total percent	1.7%	11.7%	21.7%	29.4%	23.3%	11.1%	1.1%	100.0%	
Structure type									
Bath complexes	0.5	7	11.5	10.5	3	2.5	0	35	40.2%
Villa/house structure	1	1.5	5.5	4.5	1.5	2	0	16	18.4%
Church/ecclesiastical	0	1	0.5	8.5	17	9	0	36	41.4%
Total	1.5	9.5	17.5	23.5	21.5	13.5	0	87	100.0%
Total percent	1.7%	10.9%	20.1%	27.0%	24.7%	15.5%	0.0%	100.0%	

weight in arches and vaults, (b) an increase in insulation, and (c) a solution for building forms when wood is scarce and/or costly. Studies have indicated that amphoras used in vaults provide a negligible reduction in overall structural weight, although there is a reduction in cartloads of materials needed for producing concrete.[29] The use of mortar to join vaulting tubes created a relatively thin air pocket and undoubtedly had a similarly minor effect on overall vault weight. The internal space of vaulting tubes, often partially filled with mortar and plaster, had a small and irregular air pocket that did not produce a particularly good insulation layer. Moreover, the solid areas between adjacent tube chains would diffuse heat, and voids of >1 cm must have allowed for significant convection transfer of heat. Hollow bricks used in bath complexes were designed to transfer heated air; the small nozzles of vaulting tubes, often blocked with mortar, could not function in this capacity.

It may be that the use of vaulting tubes arose in an economy where wood was scarce and thus less economical for the construction of concrete forms. A strain on wood supply can be inferred from the evidence for agricultural fuel in kilns in Tunisia.[30] Demand for wood as fuel (*lignum*) came from public bath complexes and the smelting and glass industries; demand for wood as medium (*materia*) came from furniture and tool manufacturers and shipbuilders. Demand for wood as both lignum and materia led to it being shipped overseas as a trade good, including from Tunisia.[31] A rise in wood costs gave vaulting tubes a comparative advantage for construction projects as early as the late first century, and this technology proliferated North Africa during the second and third centuries. The coarseware industry expanded rapidly in Tunisia during the third century and into the fourth, and ceramic vaulting tubes could have been fired from the same clay and in the same kilns typically used for coarseware production. With kilns burning agricultural waste, wood could be bypassed altogether in the manufacturing and construction processes.

Vaulting Tube Metrics

No publication known to the author has presented comprehensive measurements of published vaulting tubes, which are summarized in table 11.2.[32] Early typological analysis was conducted by Durm[33] and later by Lézine. Peacock noted that the vaulting tubes from Carthage were generally in two size classes based on total length, short and long; the shorter ones were between 13.0 and 14.0 cm, while the longer one was just over 18.0 cm; most examples were between 13.0 and 15.4 cm and thus within his "short" category.[34] Eleven examples from the Levanzo 1 wreck were recovered and measured, and their dimensions, along with those from other published or furnished examples, are provided in table 11.2. Of the 22 complete examples, 20 fall within the range of maximum length dimensions associated with Peacock's small category. The remaining two are significantly larger.[35]

Although the sample size is small and undoubtedly has different origins, there is remarkable consistency in the form and dimensions of the tubes, particularly those in the small category. The vaulting tubes from the Levanzo 1 wreck, assumed to be from a single source, are consistent in their overall dimensions, particularly their body and nozzle lengths. This is logical in that their dimensions needed to be consistent in order to interlock and function as a vault form. Hence, a simple system of in which there existed two sizes of vaulting tubes, "short," <16.0 cm, and "long," ≥16.0 cm, seems adequate at this point. Later vaulting tubes produced in Italy are typically larger; for example, those from the church of San Geovanni Domnarum in Pavia are 21–23 cm in length.[36] The greatest variation in vaulting

Table 11.2. Vaulting tube measurements

Artifact Number	Maximum Length	Body Length	Max. Body Diam.	Body Thck.	Open End Diam.: Inner	Nozzle Length	Nozzle Diam.: Max.	Nozzle Diam.: Min.	Nozzle Open Diam.: Inner	Avg. Ridge Spacing	Max. L:D Coeff	Body: Nozzle L.
Levanzo 1 Wreck: SI06AA-0003	13.1	8.9	5.3	0.7	4.1	4.2	3.5	2.1	1.3	1.3	2.47	2.12
Levanzo 1 Wreck: SI06AA-0005	13.8	9.3	5.9	0.5	4.3	4.5	3.5	2.1	1.5	1.5	2.34	2.07
Levanzo 1 Wreck: SI06AA-0006	13.3	9.0	5.1	0.7	3.7	4.3	2.7	2.2	1.6	1.1	2.61	2.09
Levanzo 1 Wreck: SI06AA-0007	13.6	9.0	5.4	0.6	4.1	4.6	3.2	2.1	1.3	1.0	2.52	1.96
Levanzo 1 Wreck: SI06AA-0016	13.3	9.0	5.4	0.5	4.1	4.3	3.2	2.7	1.6	1.3	2.46	2.09
Levanzo 1 Wreck: SI06AA-0025		9.4	5.5	0.4	4.7					1.1		
Levanzo 1 Wreck: SI06AA-0026	13.6	9.3	5.2	0.7	3.8	4.3	3.1	1.9	1.6	1.1	2.62	2.16
Levanzo 1 Wreck: SI06AA-0027		8.9	5.2	0.5	4.2		3.3			0.7		
Levanzo 1 Wreck: SI06AA-0029	13.5	9.2	5.5	0.4	4.3	4.3	3.0	2.0	1.3	1.5	2.45	2.14
Levanzo 1 Wreck: SI06AA-0030	13.4	9.1	5.4	0.4	3.9	4.3	3.1	2.1	1.3	1.1	2.48	2.12
Levanzo 1 Wreck: SI06AA-0031	13.0	9.0	5.3	0.4	3.9	4.0	3.3	2.1	1.3	1.1	2.45	2.25
Pt. del Fenaio Wreck (Bound fig 14)	14.4	10.0	5.7	0.8	4.9	4.4	4.4	2.5	1.0	1.5	2.53	2.27
Scoglio della Sirena Wreck (Medaglia and Rossi 2010, fig 3.32)	13.0	9.7	5.2	0.8	4.2	3.3	4.0	1.9	0.8	1.2	2.50	2.94
Scoglio della Sirena Wreck (Medaglia and Rossi 2010, fig 3.33)			4.8	0.6	3.2					1.1		
Marsala Harbor (Bound fig 8)	14.3	9.6	5.7	0.7	4.1	4.7	3.7	1.7	0.2	1.3	2.51	2.04
Marsala Harbor (Bound fig 9)	15.3	10.8	6.2			4.7	3.5	1.7		1.6	2.47	2.30
Unk. Proven. (Bound fig 16)	15.4	10.8	5.7	0.9	3.7	4.6	4.2	1.6	0.6	0.8	2.70	2.35
Tunisia (Peacock fig 92.1)	13.2	9.6	4.8	0.6	3.4	3.6	3.3	1.6	0.2	1.0	2.75	2.67
Tunisia (Peacock fig 92.2)	13.8	9.6	5.6	0.9	3.4	4.2	3.6	1.9	0.2	1.0	2.46	2.29
El Jem (Bonifay 2004 fig 249.1)	12.6	7.5	4.9			5.1	2.8	1.2		1.5	2.57	1.47
Chaal (Bonifay 2004 fig 249.2)	10.9	7.0	4.9			3.9	3.2	1.0		1.2	2.22	1.79
Carthage (Hayes 1976 fig 2, V.19)	12.9	9.1	5.0	0.6	3.7	3.8	3.2	2.0	1.2	1.2	2.58	2.39
Oued R'mel (Bonifay 2004 fig 249.4)	13.2	9.4	5.0			3.8	2.9			0.9	2.64	2.47
Jdidi (Bonifay 2004 fig 249.5)	14.7	10.9	5.4	0.7	3.4	3.8	2.9	1.8	0.2	0.9	2.72	2.87
Levanzo 1 Wreck Average	13.40	9.10	5.38	0.53	4.10	4.31	3.19	2.14	1.42	1.16	2.49	2.11
Levanzo 1 Wreck St. Dev.	0.25	0.17	0.21	0.13	0.28	0.17	0.24	0.22	0.15	0.23	0.08	0.08
Small (10.0-15.5 cm) Average	13.54	9.31	5.34	0.62	3.96	4.22	3.35	1.91	1.01	1.17	2.53	2.23
Small (10.0-15.5 cm) St. Dev.	0.97	0.89	0.35	0.16	0.44	0.42	0.44	0.39	0.53	0.24	0.12	0.33

tubes is found in the thickness of the walls and, consequently, the opening at the end of the nozzle; this is the least important dimension to maintain consistency in order to fit them together. The nozzle openings are small and would have easily become clogged during joining; whether clogged or not, these openings were clearly not designed for air or water flow.

Vaulting Tubes on Shipwreck Sites

Based on the discovery at Carthage of vaulting tubes of local Tunisian fabric, Peacock suggested that they may have been a regional trade item.[37] The discovery of a consignment on the Levanzo 1 wreck indicates that they were indeed an overseas trade item. There are at least 16 shipwreck sites from the Mediterranean that have unattached vaulting tubes with no evidence of mortar. These are the Giglio Porto,[38] Punta del Fenaio,[39] Scoglio della Sirena,[40] and Acque Chiare[41] wrecks from Italy; the Femina Morta,[42] Trapani,[43] Himera,[44] Cefalù,[45] and Levanzo 1 wrecks from Sicily; the Capo Carbonara B[46] and Mandriola A[47] wrecks from Sardinia; the Sud Lavezzi F[48] wreck from southeastern Corsica; the Los Escolletes B[49] and Cap Blanc[50] wrecks from southern Spain; and the Mateille A[51] and Dramont E[52] wrecks from southern France. (tables 11.3 and 11.4 summarize the wreck sites and their cargo remains.) Three wrecks have been omitted upon review. Although the Ognina A wreck was reported to have "some pieces of earthenware piping and some others made of lead,"[53] there is no specific mention of vaulting tubes in subsequent examinations of the site.[54] Likewise, the excavation evidence of the earlier Capo Graziano A[55] and Secca di Capistello[56] wrecks do not support the presence of vaulting tubes. It is difficult to ascertain from the published reports, which often contain anecdotal or incomplete information, the exact nature of the presence of vaulting tubes on the sites, but these reports show that each of the 16 wreck sites had vaulting tubes present at one time. Wilson surmised that major manufacturers in North Africa produced vaulting tubes for specific overseas shipments; however, he concluded that there was no evidence to suggest that they were a regular trade item, a position also held by Bound and Gibbins in their efforts to explain the presence of vaulting tubes aboard ships.[57] The Levanzo 1 wreck provides this evidence.

Location of Wreck Sites

An examination of the 16 wreck site locations (figs. 11.3, 11.4) reveals that 10 are located within the Tunisia–Italy route corridor, as well as 3 of the 5 stray finds recorded by Wilson. Moreover, 9 of the 10 wreck sites in this shipping corridor have operational dates in the third and fourth centuries, a time period when 13 of the 16 merchantmen operated. That the locations within the Tunisia–Italy corridor lay in its eastern and western zones is due to the fact that archaeological research has traditionally been limited to coastal waters within diving depths. The shallow coastal waters of Sicily, Sardinia, and Corsica that have been searched lie along this shipping route; consequently, the pattern of wreck site finds is a direct product of limited and biased search areas.

Recent maritime archaeological survey demonstrates that even along traditionally "coastal routes" such as the eastern Adriatic, the majority of wreck sites are typically 2 km or more offshore, a distance that places routes in waters typically between 50 and 150 m deep. Routes between open stretches of water were commonly used where waters are hundreds of meters deep. Of the 10 wreck sites in the Tunisia-Italy route corridor, 6 lie in waters of

Table 11.3. Vaulting tubes on shipwreck sites

Wreck Site	Location	Depth (m)	Est. Date	African 1 Piccolo	African 2A	African 2B	African 2C
Giglio Porto	Giglio, Italy	36–40	200–225		■		
Capo Carbonara B	S.E. Sardinia	10	200–275	■			
Punta del Fenaio	Giglio, Italy	60–75	200–300			■	
Los Escolletes B	Isla Grosa, Murcia, Spain (Cabo de Palos)	<10	200–300				
Scoglio della Sirena	Crotone, Italy	5	225–275				
Cap Blanc	Cap Blanc, Majorca	50	250–300			■	■
Femmina Morta	W. of Punta Secca, Sicily	3–4	250–300			■	■
Trapani	Trapani, Sicily	<10	250-400?				
Levanzo I	Egadi Islands, Sicily	92	275–300	■			■
Mandriola A	Mandriola, Sardinia	2	275–325		■		■
Lavezzi F	Lavezzi Isl, Bonifacio Strait, S. Corsica	7–10	300–325				
Himera	Himera, Sicily	32	300–375		?	?	?
Acque Chiare	Torre Rossa, Brindisi, Italy	5–6	300–400				
Mateille A	Gruissan, France	3	400–425				
Dramont E	S France (b/w St.-Tropez and Cannes)	40–42	420–425				
Cefalù	Cefalù	3	500–550				

10 m or less; of the 16 total wreck sites, 10 are in less than 10 m of water and 6 of those 10 are at depths of under 5 m. Of the 6 deeper wreck sites, 3 are under 40 m of depth and in locations near shore, all easily accessible to divers. Thus, the data set for the wreck sites in the Tunisia-Italy route corridor is as skewed and grossly incomplete as the dataset of ancient shipwrecks in the Mediterranean as a whole, and the shallow waters explored on this route represent less than 0.1 percent of the potential sea lanes. Although only 6 km from an island and 15 km from mainland Sicily, the Levanzo 1 wreck site demonstrates the potential for locating and analyzing deep-water sites in the center of this shipping corridor.

The six wreck sites outside of this Tunisia-Italy route corridor also prove interesting. Two of the wreck sites are located in Spain, the Los Escolletes B near Cartagena (Carthago Nova in Baetica) and the Cap Blanc wreck in the Balearic Islands. The Los Escolletes B wreck carried local Baetican amphoras and apparently was wrecked early in its voyage; although

African 2D	African 3	Dressel 30—Tunisia	Unidentified N African	Spatheion	Keay 35	Keay 55	Keay 62	Riley MRA 1	Ostia I, 455	Knossos 18	Panella 47	Almagro 51A	Almagro 51C	Beltran 72	Dr 23—Tejarillo 1	LRA 1	LRA 2	LRA 3	Agora M 326
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unknown, it is possible that this wreck was engaged in the much-frequented overseas traffic between Baetica and Tunisia. Conversely, the Cap Blanc wreck was almost certainly a merchantman en route to Spain with a last port of call in Tunisia. It is unclear how many vaulting tubes were present on this site, and a cargo of them may be unlikely given the paucity of structures in Spain utilizing vaulting tubes.

The Mateille A and Dramont E wrecks are both located along the southern coast of France (Narbonensis) and date to the beginning of the fifth century, the latest period within this data set. Given that the amphora types reported are African 3 (Keay 25), the poorly dated Acque Chiare wreck likely operated during the fourth century. Beginning its final voyage in Tunisia, its final resting place is located along a route typically associated with vessels heading toward the primary shipping route along the Adriatic's eastern coast. Although the southern half of the eastern Adriatic (Epirus Vetus, Epirus Nova, and Thessaly) came under

Table 11.4. Secondary and tertiary cargoes on wreck sites with vaulting tubes

Wreck Site	Fine Ware	Coarseware	Other	Vaulting Tubes	Cargo Origin
Giglio Porto			Iron bars	Several	Tunisia
Capo Carbonara B				At least 1	Tunisia
Punta del Fenaio				Many	Tunisia
Los Escolletes B				Many?	Spain
Scoglio della Sirena	ARS A	X		Several	Tunisia
Cap Blanc				At least 1	Tunisia, Portugal
Femmina Morta	ARS D	X		12+	Tunisia, Portugal, Spain
Trapani				Many?	Tunisia?
Levanzo I		X		150+	Tunisia, Portugal
Mandriola A					
Lavezzi F		X		At least 3	N. Africa?
Himera		X	Bronze, lead fragments	No. unreported	Tunisia, Portugal, Spain
Acque Chiare				At least 4	Tunisia
Mateille A	ARS D	X	Iron bars, bronze fragments	1	Tunisia, Portugal, Spain
Dramont E	ARS D	?		No. unreported	Tunisia
Cefalù	ARS & Aegean	X		At least 1	Tunisia

the administration of the Eastern Empire during the fourth century, the northern half (Dalmatia) remained under Western Imperial rule. Shipments from North Africa moving along this eastern Adriatic route toward the northern ports have come to light in recent work.[58] It is during the fourth century that ecclesiastical architecture utilizing vaulting tubes increases in Italy, especially along the northern Adriatic coast.

Nature of the Consignments

Initial discoveries of vaulting tubes on shipwreck sites suggested they were sparse and scattered and thus led to assumptions that they served a purpose on board the vessels. These ideas were reinforced by the unique find on the Punta Ala wreck in northwest Italy dated to ca. 250: a short section of pipe in the hold formed by vaulting tubes that was erroneously hypothesized to be part of a bilge pump system.[59] The vaulting tubes of this chain were mortared together, as they are when found within a structure. Given the extremely small opening of nozzles on vaulting tubes (table 11.2), their use as water conduits is not plausible.[60] As was common with ceramics in antiquity, it is more likely that they were taken from a demolished building and were serving a secondary use unrelated to their original structural function. Similarly, Bound surmised that although the presence of vaulting tubes on the Punta del Fenaio wreck was uncertain, the possibility existed for their use either as chocks to secure transport amphoras or to construct shelters on deck in order to protect the crew and/or cargo.[61] The use of vaulting tubes for the construction of deck structures has no known parallels from shipwreck excavations. Rigid cement structures are ill suited to wooden vessels subject to flexing, and excessive weight above deck level produced instability.

In assessing vaulting tube finds, or any small artifacts, on wreck sites, one must take into account wave action, bioturbation, depth, and looting. Wave action along coasts during typical days down to the fair weather wave base (FWWB) and during storms to the storm wave base (SWB) move and scatter small objects from wreck sites. The FWWB for northeast Sicily, for example, is approximately 10 m, and the typical SWB reaches 16 m of depth.[62] Ten of the 16 wreck sites with vaulting tubes fall within the FWWB (table 11.3). Storms are noted in Sicily to have moved boulders weighing tons tens of meters onto shore,[63] and cyclones are known in the Mediterranean[64] that can produce large waves that could disturb wreck sites in 30 to 40 m of depth. Such storms would affect 13 of the 16 wreck sites in this data set. Consequently, a scatter of vaulting tubes could be construed as chocks for larger cargo containers.

Vaulting tubes are easily moved not only by wave action but also by octopuses. As a matter of normal behavior octopuses gather small objects like vaulting tubes when constructing their nests, which are often located within amphoras. This was observed over a single year on the Levanzo 1 wreck site, and numerous small finds including vaulting tubes were discovered within the contents of raised amphoras. This underscores the need for biological study of wreck site formation to better interpret the spatial distribution of artifacts upon recording.

Depth is an important factor in assessing the effects of wave action and bioturbation but also a key factor for human disturbance. The ten wreck sites at under 10 m of depth have been accessible to humans for 1,500 to 1,800 years. Tubes are small and light and thus easy to remove from sites as souvenirs or salvage material; this is less so for larger and heavier amphoras. Taking into account the removal of vaulting tubes by wave action and human disturbance, the number of vaulting tubes on shallow wreck sites was almost certainly larger when the ships sank than when the wrecks were recorded in the twentieth century. As shown in tables 11.3 and 11.4, in general the wrecks with the lowest reported number of vaulting tube finds are the shallowest, while the Punta del Fenaio and Levanzo 1 wrecks, the deepest sites, have the largest numbers present.[65] The large number of vaulting tubes concentrated low in the hold on the Levanzo 1 wreck indicates that they were cargo and not used as chocks for amphoras. Likewise, the lack of joins or mortar among any of the tubes eliminates their previous use, as on the Punta Ala wreck. In light of the evidence from the Levanzo I shipwreck, and the potential effects of wave action, human disturbance, and bioturbation for shallow sites, a reassessment is warranted. It is suggested here that vaulting tubes on the other 15 wrecks were cargo (tertiary goods) or the remnants of a previously carried consignment.

With vaulting tubes designated as cargo on these 16 wreck sites, it is possible to evaluate them within the overall assemblages. Reports for the 16 wreck sites are inconsistent, but there is enough information to designate with some confidence the primary, secondary, and tertiary cargo components. An understanding of the primary cargo is critical as it signifies the last major port of call for each merchantman prior to the wrecking event. The reported amphora types for each wreck in table 11.3 demonstrates that their primary cargoes were commonly shipped foodstuffs, including oil, wine, and fish products.[66] As discussed, there is an indication that the Levanzo 1 wreck also carried grain in its final cargo, and it is certainly possible that other wrecks carried grain as well. In 13 of the 16 shipwrecks where specific amphora types are reported, amphoras from Tunisia comprise a majority of the cargo.

In addition to commodities carried in amphoras and grain, there were secondary and tertiary goods present in at least 9 of the 16 wrecks (table 11.4). African Red Slip (ARS) finewares were on five of the wrecks, and three of those carried ARS D, a type produced in the vicinity of Carthage[67] and the nearby northern sector of Tunisia.[68] Seven, possibly eight, of these merchantmen carried consignments of coarsewares. Hence, although it was reported that the Lavezzi F wreck carried amphoras of generic North African origin, the presence of coarseware may suggest a Tunisian origin. Similarly, the Matielle A wreck is reported to have carried North African amphoras but also fineware of form ARS D, which together point to a final port in Tunisia, alongside coarseware and iron bars. Additionally, the aforementioned Punta Ala wreck with a small vaulting tube chain not carried as cargo was wrecked near Italy during the third century with a primary cargo of Tunisian origin along with ARS C and D finewares.[69] Thus it is possible that 15 of the 16 shipwrecks made their last port of call in Tunisia, the chief region of the annona supply in the central and western Mediterranean. Only the Los Escolletes B wreck carried local amphoras, presumably with origins in southern Spain (Baetica), and certainly did not originate in Tunisia.

Diffusion of Vaulting Tube Technology

Beginning in North Africa sometime in the first century, the use of vaulting tubes peaked during the third and fourth centuries (fig 11.4). The peak in vaulting tube use in North Africa during the third and fourth centuries corresponds to the period of initial rise in the use of vaulting tubes at sites in Italy. It should be noted that the number of datable structures in Chart 1 assuredly underrepresents the total actual number of structures where vaulting tubes were employed; however, the totals do illustrate trends over time. Critically, the peak in vaulting tube use in North Africa corresponds with peak transport of vaulting tubes in the shipwreck data. All but one shipwreck were in operation in the third and fourth centuries, nearly all were carrying cargoes that originated in Tunisia, and the majority are found within the Tunisia-Italy route corridor.

By the second century the annona system was a crucial component of the Roman economic system, influencing the nature and direction of shipments. All shipping routes in the Mediterranean were either directly or tangentially shaped by the annona system. Heavy shipping along the Tunisia-Italy corridor during the second through fifth centuries brought agricultural and finished goods to Rome, with Italian brick and tile carried to North Africa. By the third century Tunisia served as an extended local economy for central Tyrrhenian Italy and eclipsed other sources in supplying Italy, and particularly Rome, during this time. This trade further intensified with the division of Imperial administration in the fourth century and the expansion of Tunisia's agro-economy, which fostered the growth of other manufacturing industries such as fineware and coarseware production.

Based on this distribution pattern of vaulting tubes in terrestrial and maritime contexts, a relationship is hypothesized between the economic structure of the annona, overseas shipping, and technology transfer. As vaulting tubes were used throughout North Africa in numerous projects both inland and coastal, there must have been centers in place that produced vaulting tubes. The peak in their use during the third and fourth centuries was undoubtedly associated with an increase in overall production. Also, at this time there was decreased demand placed on Tunisian manufacturers to produce brick and tile given the likelihood of increased return shipments from Rome. Alternatively, coarseware and fineware production increased, and the expanding agro-economy provided the fuel as wood supplies became increasingly strained. These wares found consumers throughout the Mediterranean and could be traded to meet rising consumer demand in Tunisia for imported goods as a consequence of an expanding economy.[70] The strain on wood resources that facilitated vaulting tube use in North Africa would have also been experienced in Italy and Sicily. The selection of vaulting tubes over wood prior to the third century was less frequent in Italy and Sicily, as wood was more readily accessible from local sources, yet over time decreased supplies led to increased costs.

The logistical mechanism for the diffusion of vaulting tubes was overseas shipment, specifically as small, tertiary cargoes onboard vessels contracted within the annona system. With the intensification of annona shipping along this North Africa–Italy route in the late third and fourth centuries, more secondary and tertiary goods were included in ship cargoes. Inasmuch as construction materials in general have a low profit margin, and specialized types such as vaulting tubes in particular, it would have been crucial to keep shipment costs to a minimum. The annona system created a shipment structure for *navicularii* that nearly eliminated overseas shipping costs and encouraged through incentives the inclusion of secondary and tertiary consignments. The ready supply of vaulting tubes during the third and fourth centuries provided navicularii operating within the annona system another good that had a low cost to enable profit and was physically durable for transport. Thus during the third and fourth centuries, vaulting tubes from North Africa were increasingly transported as cargo on merchantmen sailing along the Tunisia-Italy route corridor to the coastal areas of Sicily and Italy, with a concomitant diffusion of the technological knowledge to effectively utilize this construction material.

The majority of sites in Italy and Sicily where vaulting tubes were employed are restricted to the coast, and it is likely that vaulting tubes were first introduced on a small scale as the occasional consignment of opportunistic traders. Over time the technology spread farther inland and the selection of the technology increased as its cost decreased. Once demand reached a sufficient level, production at inland sites became economically feasible.

Technological dissemination requires individuals to communicate its use. The close overseas link between Tunisia and Italy, along with areas in between, facilitated this. Individuals from North Africa with expertise in vaulting tube construction could easily have traveled overseas to coastal cities in Italy and Sicily, perhaps to work on large-scale projects and possibly to settle. The movement of individuals with expertise undoubtedly took place, as we see the technical employment of vaulting tubes in construction was known in Italy and Sicily prior to the fourth century. Manufacturers in Tunisia had an initial advantage in vaulting tube production in that they already had expertise in production and use, stable demand in the North African region, and availability of ceramic production centers in place for coarseware and amphoras.

Conclusions

The evidence to date indicates that vaulting tubes were a North African innovation of the first century. The economic feasibility to ship vaulting tubes as cargo arose with the shipping routes and economic structure shaped by the annona system. The changing agro-economy and overseas route structure within the Mediterranean during the second through fourth centuries created conditions for the economical production, use, and dissemination of vaulting tube technology. At this time Rome's local economy enlarged to incorporate Tunisia, Sicily, Sardinia, and southwestern Calabria. The intensification of overseas annona shipments along the Tunisia-Italy route corridor was contemporaneous with the transport of vaulting tubes from North Africa and the rapid increase of their use in construction in Italy and Sicily. This model explains the spread of vaulting tube technology, the timing of their use, the predominant coastal versus inland location of sites in Sicily and Italy, the concentration of wreck sites with vaulting tubes located along the Tunisia-Italy route corridor, and the high correlation of North African cargoes for these wreck sites. The distribution pattern of vaulting tubes serves as an indicator for the extended local economy of Rome.

NOTES

1. The ongoing project focuses on the coastal waters around the Egadi; large areas of seafloor with intensive remote-sensing survey and ROV inspection.

2. Royal and Tusa, 2011. This article includes a full discussion of the methodologies employed in the mapping, excavation, and recording of the site. Ongoing updates on the EISP can be found at www.rpmnautical.org/sicilian.

3. As noted, the ceramic concentrations on the Levanzo 1 wreck site are in the northwest and southeast zones of the wreck site, while absent in the central area between them (Royal and Tusa 2011). The nails and timber fragments locate in this central sector, along with the overall site dimensions, indicate that the hull was deposited as a unit. A logical conclusion, although an admitted argument by absence, is that a perishable cargo (grain) was carried in the central hold. Given that North Africa was an important source of grain for Italy, the military, and other large provincial cities during the Imperial era and one of the primary foodstuffs carried on merchantmen along this route, the inference is certainly plausible. Rickman suggests that merchantmen carried grain loaded in dolia or sacks or separated by bulkheads within the hold in order to maintain ownership designations (Rickman 1980; Fulford 1987, pp. 261–62). There were no signs of dolia on the Levanzo 1 wreck site, but sacks or bulkheads would not have survived in the archaeological record. Products shipped in amphoras were often secondary in proportion to the grain cargo carried out of North African regions such as Mauritania, which assuredly was the case for many shipments originating in Africa Proconsularis as well. Consequently, merchantmen carrying grain had fewer amphoras in their cargo compared to merchant with cargos of primarily oil, wine, and/or fish products, a case that corresponds with the Levanzo 1 wreck site. Preliminary typology identifications for the tableware include Bonifay common type 47 and 50 flagons, and the plate is analgous to Bonifay cookery (B) type 6 (Bonifay 2004, 280–85, pp. 216–17), forms commonly produced in Tunisia during the Late Roman period. Found within the amphoras were a base of a glass bottle or small jug, a base of a glass bowl/plate, and a glass body fragment.

4. A high-resolution three-dimensional site plan produced in 2012 resulted in an increased estimated total for the square deposit.

5. Lézine 1954, pp. 168–81; Peacock 1984, pp. 242–46, figs. 92–1, 92–2; Wilson 1992, pp. 97–129.

6. Royal and Tusa 2011.

7. Royal and Tusa 2014, "New Amphora Contexts and a Re-Dating of the Levanzo 1 Wreck," forthcoming.

8. Bonifay, personal communication, May 2013.

9. Bonifay 2004, p. 150, fig. 62.

10. Beltrán Lloris 1970, p. 542, fig. 221.

11. Lequément 1976.

12. Liou 1974.

13. C. Franco, personal communication; Franco, forthcoming; a fabric sample has been taken for petrologic analysis to clarify the identification.

14. Bonifay, personal communication, forthcoming.

15. Lézine 1954, pp. 168–81; Olivier and Storz 1982, pp. 111–27; Wilson 1992.

16. Lézine 1954, p. 173.

17. Bovini 1960, p. 93; Lézine 1954, pp. 168–81.

18. Lézine 1954, p. 169.

19. Arslan 1965: pp. 45–52.

20. Rakob 1982: pp. 107–15, tavv. 26–27.
21. Wilson 1992, Appendix.
22. Tomasello 2005.
23. Peacock 1984, pp. 15, 245–46; the vaulting tubes were classified as fabric 2.2, pp. 15–16 (same volume).
24. Medaglia and Rossi 2010, p. 515.
25. Royal and Tusa 2011, pp. 44–45. A fabric sample is under petrologic analysis that will be related in a subsequent publication.
26. Dodge 2011, p. 476.
27. Bound 1987, pp. 187–200.
28. For a complete list of vaulting tube finds from land sites, see Wilson 1992, pp. 125–29, Appendix.
29. Lancaster 2005, pp. 75–80.
30. Stirling and Ben Lazreg 2001, pp. 227–28; Smith 2001, pp. 434–35; Ikäheimo 2005; Wilson 2012, pp. 149–50.
31. Wilson 2012, pp. 149–50.
32. Bound 1987, pp. 187–200, figs. 1, 2; Más García 1985, pp. 164–68; Lézine 1954, pp. 168–81; Peacock 1984, pp. 242–46, figs. 92–1, 92–2; Wilson 1992, pp. 97–129; Medaglia and Rossi 2010; Royal and Tusa 2011, pp. 44–45.
33. Durm 1905, pp. 296–302, figs. 320–24.
34. Peacock 1984, p. 245.
35. According to Arslan 1965, pp. 46–47, specimens from Forli had 12.0- to 13.5-cm maximum lengths, maximum diameters of 0.6 to 0.7 cm, nozzle lengths of 6.5 to 7.0 cm, and body thicknesses of 0.5 to 0.6 cm. Examples from an undated structure in Rimini averaged 14.5 cm in length, maximum diameters of 6.5 to 7.0 cm, had nozzles of 5.5 to 7.0 cm in length, and were 0.5 to 0.6 cm in body thickness.
36. Arslan 1965, p. 45.
37. Peacock 1984, pp. 245–46.
38. Ciabatti 1985.
39. Bound 1987, pp. 187–200.
40. Spanu and Ignazio 2006, p. 183.
41. Sciarra Bardaro 1973; Gibbins 1989, p. 242, note 12.
42. Parker 1977, pp. 624–28.
43. The reference to "Trapani" wreck is to designate a wreck site under investigation by the Soprintendenza del Mare, Sicilia that has not been published. I thank S. Tusa for information on this site and the presence of vaulting tubes.
44. Gibbins, 1991, p. 242, note 12.
45. Purpura 1983.
46. Fennell 1974, pp. 331–32.
47. Medaglia and Rossi 2010.
48. Tchernia 1969, pp. 465–99.
49. Más García 1977, pp. 277–78; Más García 1985, pp. 153–71.
50. Gibbins 1991, p. 242, note 12; Parker 1992, p. 99.
51. Gibbins 1991, p. 242, note 12.
52. Joncheray 1975, pp. 141–46; Gibbins 1991, p. 242, note 12.
53. Gargallo di Castel Lentini 1972, p. 445.
54. Kapitän 1972, 1973.
55. Cavalier 1985.
56. Frey et al. 1978.
57. Wilson 1992, p. 120; Bound 1987, p. 192; Gibbins 1989, pp. 3–4.
58. Royal 2012; Royal forthcoming.
59. Lamboglia and Pallarés 1983, pp. 172–76.
60. Bound (1987, p. 192) came to the same conclusion. Vaulting tubes are not employed as water conduits in any known context.

61. Bound 1987, p. 192.
62. Messina et al. 2009.
63. Barbano et al. 2010.
64. Reed et al. 2001.
65. Exacting estimates for the numbers of vaulting tubes on sites is difficult to ascertain from the reports. Gibbins does not qualify their reported presence on the Cap Blanc wreck site as to the relative number of tubes present on the site that is at 50 m of depth. Gibbins 1991, p. 242, note 12. Likewise, the total number of tubes and their provenience to other finds is not clear for the Sud Lavezzi F and the Acque Chiare wrecks (Tchernia 1969, pp. 465–99; Bound 1987, pp. 187–200; Sciarra Bardaro 1973, pp. 341–52; Gibbins 1991, pp. 227–46).
66. Notably, the cargo composition of the Himera wreck site is somewhat uncertain.
67. Hayes 1980, p. 518; Riley 1981.
68. Mackensen 2009, pp. 18–20.
69. Lamboglia and Pallarés 1983.
70. Fulford 1984, pp. 257–58.