Building Trajan's Column

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Abstract

Trajan's Column is best known for its sculptured spiral frieze celebrating Trajan's victories in the Dacian Wars, but it is also a complex architectural monument representing an impressive feat of engineering. The Column is made up of 29 blocks of Luna marble weighing from 25 to 77 tons, the highest of which had to be raised to 38.4 m above ground. In this paper I discuss the evidence both for the construction of the Column and for the organization of the building site. Excavations earlier in this century revealed an unusual use of brick ribbing in the vaulted substructures of the north portico, which I propose was intended as reinforcement for the vaults over which the individual blocks of the Column were maneuvered before being lifted into place. This implies that the work site for the blocks lay to the north of the Column courtyard (where the later Temple of Divine Trajan is traditionally located), which is the area most easily accessible from any unloading point along the Tiber. Finally, I propose a hypothetical reconstruction of a lifting device for the blocks making up the Column based on comparative evidence from other sites, on ancient literary descriptions of building methods, and on calculations of the bearing capacities of timbers, ropes, and capstans.*

Trajan's Column, which once supported a bronze statue of that emperor, stands 38.4 m high to the top of the statue base and is made up of 29 blocks of Luna marble together weighing over 1100 tons. Although the monument is best known for its sculptured spiral frieze telling the story of Trajan's victories in the Dacian Wars of A.D. 101–106, it also represents an impressive feat of construction that bears witness to the technological and organizational skill of the builders.

In the following discussion I examine the on-site archaeological evidence for the construction of the Column, compare it to evidence from other sources (both literary and archaeological), and propose a hypothetical reconstruction of the lifting device used to raise the marble drums of the Column shaft as a means of exploring the complex nature of the building process. Calculations of material weights and stresses are used to check the feasibility of the proposals. Finally, I examine the logistical problems of transporting the building materials to the site and the organizational forethought required for such a complex endeavor in the heart of a major urban center.[1]

THE COLUMN AND ITS COURTYARD

The Column was part of the monumental forum complex built by Trajan (ca. A.D. 106–113). It is located to the north of the Basilica Ulpia between the east and west rooms of the Bibliotheca Ulpia and stood in a courtyard surrounded on three sides by porticos (fig. 1). As noted in the *Fasti Ostienses* and confirmed in the inscription on its pedestal, the Column was dedicated in May A.D. 113, over a year after the dedication of the Basilica Ulpia in January A.D.

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* I am grateful to Lucrezia Ungaro and Roberto Meneghini of the X Ripartizione AA.BB.AA of the Comune di Roma for allowing me to examine the areas around the Column of Trajan and to Giangiacomo Martines and Cinzia Conti of the Soprintendenza Archeologica di Roma for providing access to the Column itself. Clayton Fant kindly provided me with information about Luna marble. During the course of preparing this article, I learned a tremendous amount from watching and talking to our building contractor Bill Fanning and his crew, Lynn Shaw, Jerry Moleski, and Charlie Laidlaw-Smith, as they erected scaffolding, substituted beams, and then raised and leveled floors in our house. For reading drafts of this paper, I thank Amanda Claridge for providing invaluable comments both on the topography of Rome and on marble working, Mark Wilson Jones for his comments on the design and construction of the Column, Carla Maria Amici for her insights on Roman building, Tom Carpenter for saving me from many a non sequitur and for his willingness to read this paper over and over, and especially Jim Coulton for his eagerness to grapple with the technological and structural minutia involved in trying to reconstruct the lifting tower for the Column. The submitted version of this paper also benefitted greatly from the comments of Jim Packer and another anonymous *AJA* reader. Though many of the ideas presented here are the result of conversations with others, the reconstruction is my own and my readers do not necessarily agree on all details. The M. Aylwin Cotton Foundation generously helped fund my time in Rome. All drawings and photographs are my own unless otherwise indicated. Many of my drawings were made with the aid of AutoCad R12.

[1] Mark Wilson Jones has explored the implications of the design process on the final form of the Column of Trajan, and I do not deal extensively with those issues in this study. I am grateful to him for providing me with a draft of the chapter on Trajan's Column from his forthcoming book, *Principles of Roman Architecture* (Yale).

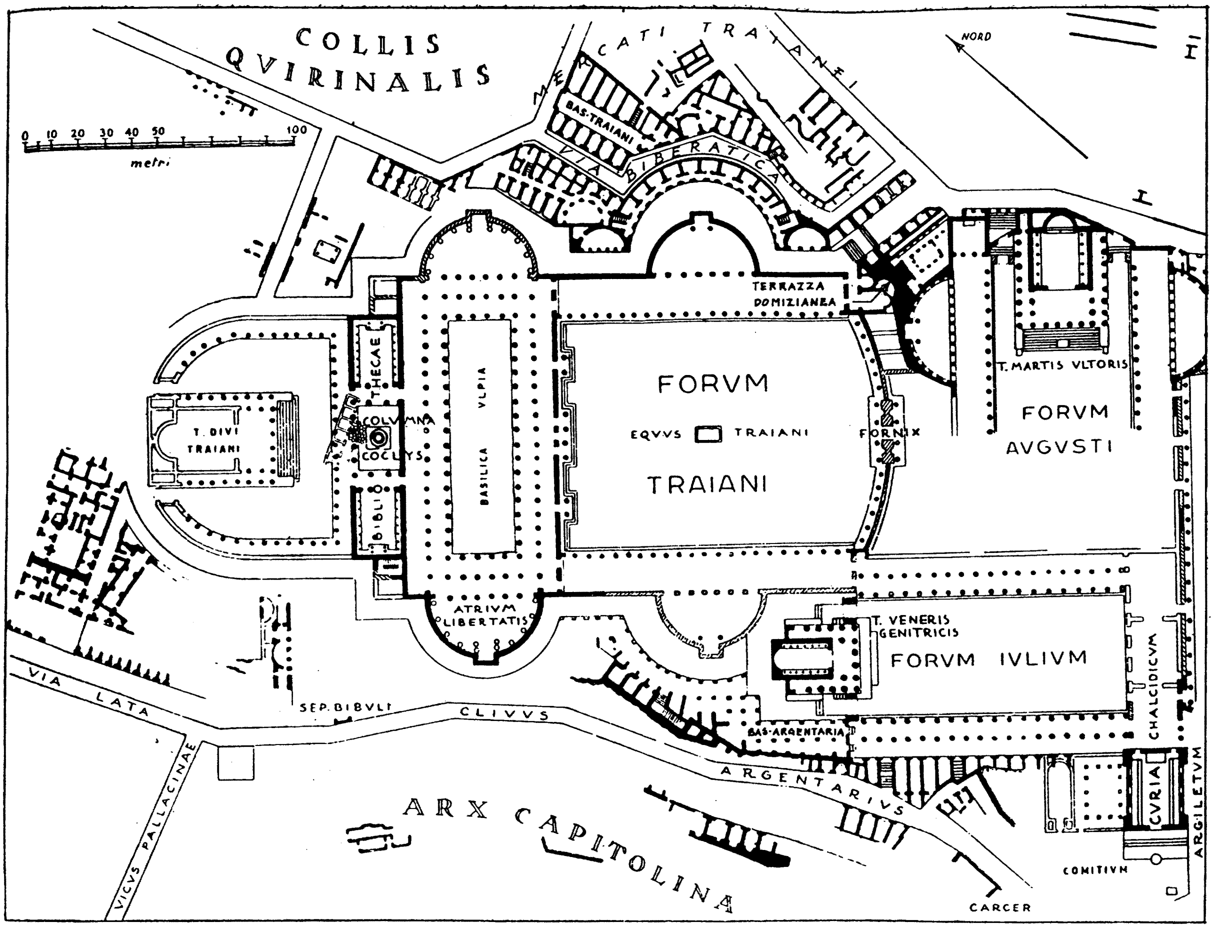

Fig. 1. Plan of the Imperial Fora by I. Gismondi. (Adapted from G. Lugli, *Roma Antica. Il centro monumentale* [Rome 1956] pl. V)

112, also recorded in the *Fasti Ostienses*.[2] Dio Cassius notes that Trajan built the libraries along with his Column.[3] The three brick stamps found in situ in the walls of the libraries all date to the Trajanic period and are found in other Trajanic buildings,[4] thereby providing support to Dio's claim.[5] The area to the north of the Column traditionally has been associated with the Temple of Divine Trajan, which is attested by an inscription giving a Hadrianic date,[6] though the precise layout of this area is still a debated issue (see below).[7]

The inscription on the pedestal of the Column states that it was set up "*ad declarandum quantae altitu-*

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[2] The pedestal inscription (*CIL* VI, 960) gives a date of A.D. 113 during Trajan's sixth consulship and his 17th holding of tribunician power. A fragment of the *Fasti Ostienses* records that something described in seven or eight letters ending in *m* was dedicated in the Forum of Trajan in May, A.D. 113: L. Vidman, *Fasti Ostienses: edendos, illustrandos, restituendos, curavit* (Prague 1982) 48, pls. 10, 13. G. Calza, "Un nuovo frammento di Fasti Annali (anni 108–113)," *NSc* 8 (1932) 201 restored the word as *columnam.* This restoration has generally been accepted though it is not conclusive.

[3] Dio Cass. 68.16.3.

[4] *CIL* XV, 58, 811d, and 32; H. Bloch, *I bolli laterizi e la storia edilizia romana* (Rome 1947) 58–59 (reprinted from *BullCom* [1936–1938] 64–66).

[5] During the excavations of the 1930s, 39 bricks with Trajanic stamps and 55 with Hadrianic stamps were found loose in the area of the libraries: Bloch (supra n. 4) 58–59. The existence of the Hadrianic stamps has led to speculation that the libraries were built under Hadrian: L. Richardson, "The Architecture of the Forum of Trajan," *ArchNews* 6:4 (1977) 106–107; however, both the literary evidence and the Trajanic brick stamps found in situ support the view that the libraries were begun under Trajan.

[6] *CIL* VI, 966. The inscription can be dated to the years between A.D. 123, when the empress Plotina died, and A.D. 127/8 on the basis of the titles attributed to Hadrian: C. Leon, *Die Bauornamentik des Trajansforums* (Vienna 1971) 39.

[7] J.E. Packer, "Trajan's Forum Again: The Column and the Temple of Trajan in the Master Plan Attributed to Apollodorus(?)," *JRA* 7 (1994) 163–82. For the most recent discussion of the archaeological evidence from this area, see R. Meneghini, "Templum Divi Traiani," *BullCom* 97 (1996) 47–88.

dinis/mons et locus tant(is ope)ribus sit egestus" ("in order to show how lofty had been the mountain—and the site for such mighty works was nothing less—which had been cleared away").[8] Before the excavation of the area around the Column, this passage was taken to indicate that there was originally a hill connecting the Capitoline and Quirinal, and that Trajan excavated it to create a flat plane for his Forum, but excavations conducted by G. Boni in 1906 and by C. Ricci in 1934 revealed that the Column was not built on virgin soil. Boni discovered the remains of a road paved in selce that was cut by the foundations of the Column (fig. 2:C).[9] The excavations of 1934 later revealed pre-Trajanic structures largely consisting of brick-faced walls forming a portico and a series of rooms flanking the road (fig. 2:B).[10] Since all of these structures date from the Julio-Claudian period or earlier, the "mountain" mentioned in the inscription was evidently not located on the spot where the Column was built. The term may have referred to the slopes of the Quirinal excavated for the construction of Trajan's Markets, which were also part of the same building project. Some Domitianic structures at the south end of Trajan's Forum (i.e., the Terrazza Domizianea and the lower part of the retaining wall of the Basilica Argentaria, fig. 1) have prompted the suggestion that the hill was actually excavated by Domitian and that Trajan's Forum may have even been begun earlier under this emperor.[11] The Trajanic remains, however, are built on a different alignment than the Domitianic ones and show that the design of Trajan's Forum was clearly different from any scheme that Domitian may have had in mind, though it is conceivable that some excavation had occurred by the time Trajan became emperor.[12] The builders of Trajan's Forum and Column clearly had to deal with the preexisting structures both to the south and to the north in the Column courtyard as they were preparing the site for the Trajanic complex.

In his published report of the 1906 excavations in the Column courtyard, Boni noted that the concrete foundation of the Column cut through the 70-cm thick setting bed (composed of peperino, selce, travertine, marble, and limestone) that had been laid as a base for the marble paving of the Column courtyard. The trench (12–20 cm wide) between the edge of the setting bed and the foundation of the Column was then filled with a mixture of selce and mortar made with red pozzolana.[13] The relationship of the fill to the foundation has been taken to imply that the Column was an afterthought and not part of the original plan.[14] It should be noted, however, that the only remains of the white marble paving occur along the west side of the courtyard well away from the foundation (fig. 2:E). Boni never suggested that the foundation of the Column cut through the final marble paving of the courtyard. In fact, there is no evidence that the marble paving was laid before the Column foundation was added. The setting bed would simply have established a stable and level platform so that men and materials could easily access the building site. The presence of preexisting structures in this area would have required a great deal of site preparation before the heavy work of constructing the Column began. The Column foundation, therefore, need not be explained as an "afterthought"; rather, it should be seen as part of the logical sequence of construction on a difficult and complex site.

The porticos surrounding three sides of the Column courtyard are supported on concrete vaulted substructures. The use of the vaulted substructures is an indication of the extraordinary amount of effort directed towards preparing the site. Typically, older walls, such as the pre-Trajanic ones here, would sim-

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[8] *CIL* VI, 960 (trans. F. Lepper and S. Frere, *Trajan's Column: A New Edition of the Cichorius Plates* [Gloucester 1988] 20).

[9] G. Boni, "Esplorazione del Forum Ulpium," *NSc* 4 (1907) 366 fig. 4 shows the road located ca. 1.35 m (ca. 15.52 masl) below the Column's travertine foundation cap.

[10] C.M. Amici, *Foro di Traiano: Basilica Ulpia e Biblioteche* (Rome 1982) 58–61.

[11] J.C. Anderson, *The Historical Topography of the Imperial Fora* (Brussels 1984) 147–50; M. Bianchini, "I Mercati di Traiano," *Bollettino di Archeologia* 8 (1991) 111–21; C.F. Giuliani, "'Mercati' e Foro Traiano: un fatto di attribuzione," *Quaderni dell'Istituto di Storia dell'Architettura* 1987, 25–28.

[12] Terrazza Domizianea: E. Tortorici, "La 'Terrazza domizianea', l'aqua Marcia ed il taglio della sella tra Campidoglio e Quirinale," *BullCom* 95:2 (1993) 7–24; Basilica Argentaria: C.M. Amici, *Il Foro di Cesare* (Florence 1991) 67–74. For a discussion of the controversy regarding the relationship between the Domitianic and Trajanic projects, see L.C. Lancaster, "The Date of Trajan's Markets: An Assessment in the Light of Some Unpublished Brick Stamps," *BSR* 63 (1995) 25–44.

[13] Boni (supra n. 9) 400 fig. 3.

[14] Lepper and Frere (supra n. 8) 15. A. Claridge, "Hadrian's Column of Trajan," *JRA* 6 (1993) 20 expresses some reservation on the validity of this interpretation, while C. Amici (supra n. 10) 58 n. 4 notes Boni's observation and its implications but suggests that the constructional requirements in this unusual situation may indicate an alternative interpretation. Richardson (supra n. 5) 106 proposed that Hadrian moved the Column from the east hemicycle of the Forum of Trajan to its present location, but this lacks any evidence and defies all reason.

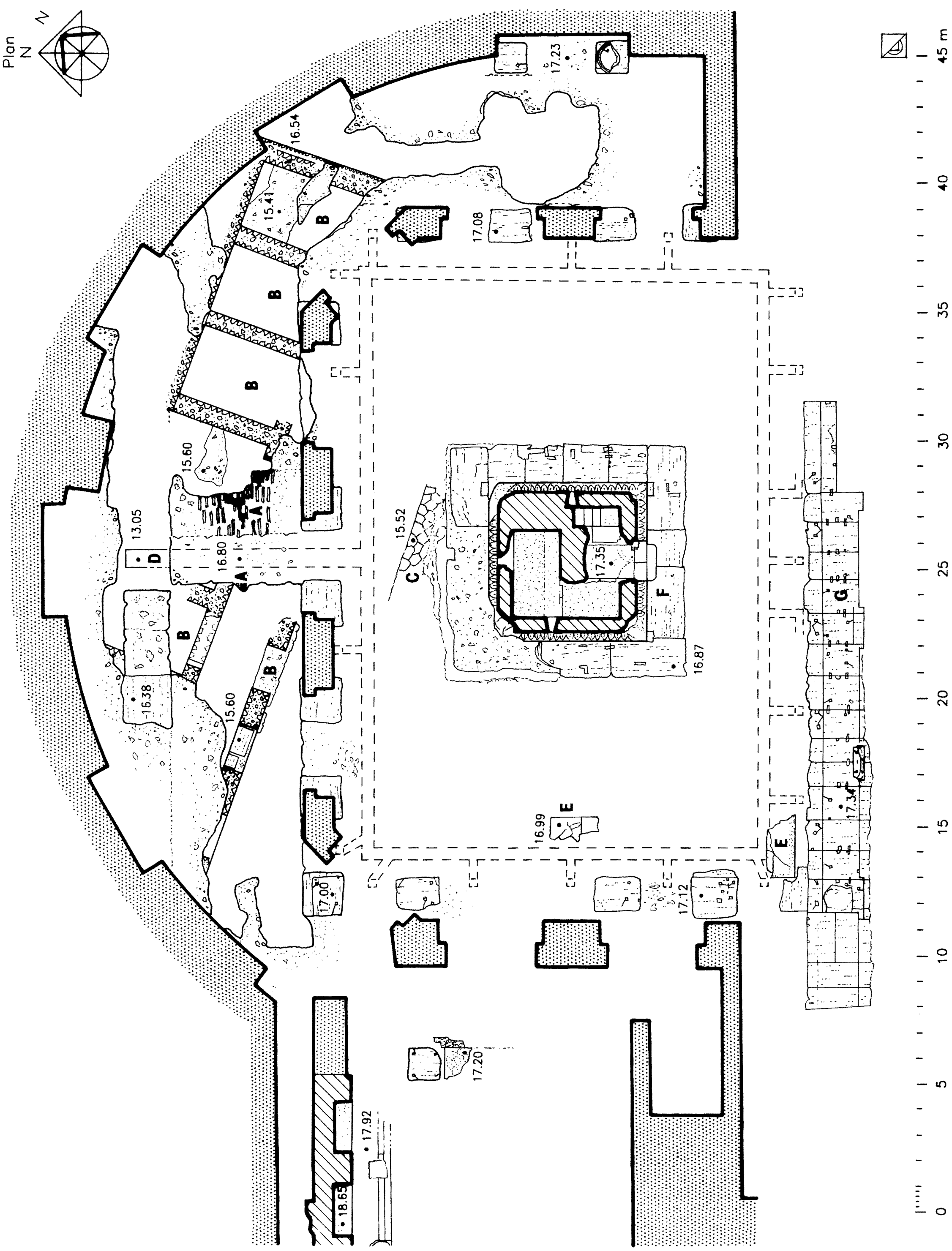

Fig. 2. Plan of the remains in the Column courtyard. (Adapted and redrawn based on C.M. Amici, *Foro di Traiano: Basilica Ulpia e Biblioteche* [Rome 1982] fig. 92, pl. 1; G. Boni, "Esplorazione del Forum Ulpium," *NSc* 4 [1907] figs. 3 and 4; and J.E. Packer, *The Forum of Trajan in Rome. A Study of the Monuments* [Berkeley 1997] fols. 0, 1, and 2). Heights are indicated by dots and are given in meters above sea level. Sections through Trajanic structures are hatched. Sections through the 1812–1814 structures are stippled. A) brick ribbing, B) pre-Trajanic structures, C) remains of pre-Trajanic road, D) drain, E) remains of white marble paving slabs, F) travertine foundation cap of Column, G) travertine foundation cap of Basilica Ulpia wall. Scale 1:250.

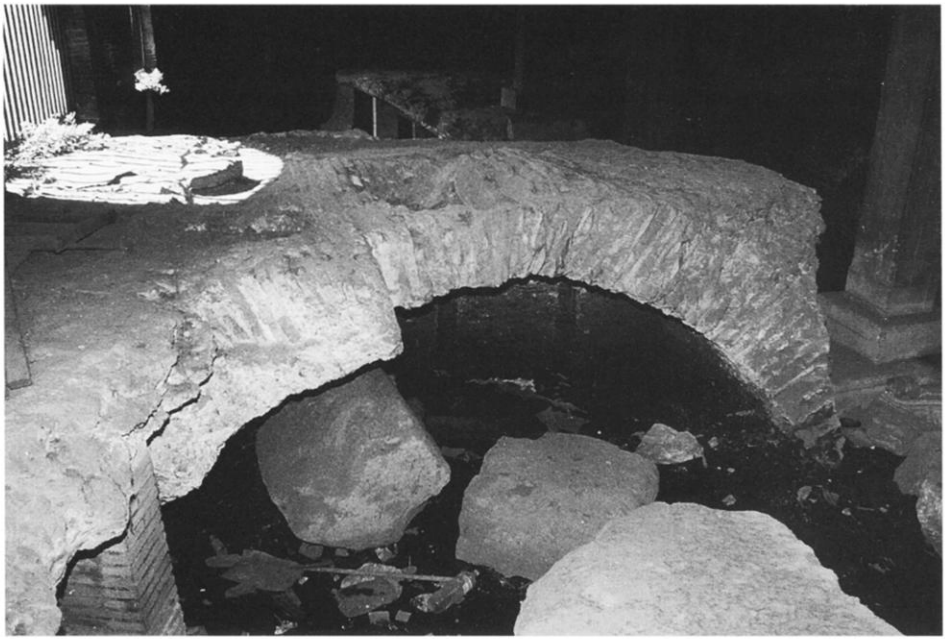

Fig. 3. Photo of the remains of the bipedalis ribbing in the substructure vault of the north portico of the Column courtyard. The opus caementicium drain wall is visible in the background under the vault.

ply have been razed, backfilled, and then sealed under the floor of the new building.[15] In the Column courtyard, the builders chose to raze the earlier walls to an appropriate height and then to entomb them in the barrel vaulted substructures. As C. Amici points out in her monograph on the Basilica Ulpia, the builders presumably wanted to avoid the possibility of the uneven settling of the backfill and to ensure an added degree of stability to this area.[16]

An unusual constructional detail in the vaults gives a clue as to how the building site was organized. The central section of the substructure vault of the north portico was reinforced with ribs of *bipedales*, large two-foot bricks (figs. 2:A and 3). Brick vaulting ribs were employed in Roman construction at least by the early Flavian period, when they were used at the Colosseum to reinforce vaults that supported the dead load of other heavy structures above.[17] The brick ribbing of the north portico of the Column courtyard is unusual because it appears to support no obvious dead load. It occurs on either side of a 1.80–1.90-m thick wall of *opus caementicium*, into which has been built a drain, 0.70 m wide and 1.50 m high, which collected the runoff from the portico roof. The ribbing to the east of the wall continues for a length of 2.30 m at which point the construction of the vault reverts to the typical opus caementicium consisting of pozzolana/lime mortar binding chunks of tuff. The vault to the west of the wall is less well preserved, but a few remaining bipedales show that similar ribbing was also on this side.

Amici was the first to note the unusual use of the brick ribbing in the central section of this vault and to offer a possible explanation for its appearance: she suggests that the ribs were used to reinforce the area in front of a single doorway in the north wall, which would have caused an increased concentration of visitors at this spot.[18] The existence of these anomalous ribs certainly requires explanation, but I offer another interpretation. Rather than reinforcing the vault against human traffic, the ribs may have been added to reinforce the vaults against the weight of the 29 large marble blocks used to construct the Column. The weight of the maximum number of hu-

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[15] E.g., the structures under the Domus Flavia on the Palatine: C.F. Giuliani "Note dell'architettura delle residenze imperiali dal I al III secolo d. C.," *ANRW* 12:1 (1982) 246–54, pl. V.

[16] Amici (supra n. 10) 64.

[17] L.C. Lancaster, "Reconstructing the Restorations of the Colosseum after the Fire of 217," *JRA* 11 (1998) 153–54.

[18] Amici (supra n. 10) 66.

mans who could fit on the reinforced area of the vault could only reach about five tons, whereas the heaviest block of the pedestal of the Column weighs about 77 tons. Seen in this light, the extraordinary precautions taken by the builders to avoid settling problems are understandable.

The two brick ribs in the vault of the north portico substructure, when combined with the thickness of the drain wall bisecting them, have a total width of ca. 6.4 m, which is slightly wider than the pedestal of the Column (6.2 m). The base block of the Column is ca. 4.9 m in diameter, and the blocks making up the shaft are somewhat smaller; therefore, each of the blocks could fit within the reinforced area of the vault. The brick ribbing and the drain wall seem to have been designed as a type of "bridge" over which the blocks of the Column could be maneuvered before they were lifted into place. Since concrete acquires its strength slowly over a period of time,[19] the builders may have decided to use the drain wall as the primary support for the blocks and the brick ribbing to either side as reinforcement for the flanking vaults during the building process while the mortar was still curing.

This interpretation of the brick ribbing implies that the blocks were arriving from the area north of the Column courtyard, which given the position of the Basilica and Libraries may have been the only side from which easy access was possible.[20] A work site for the preparation of the blocks must have existed in the vicinity. Some details of the design and construction of the Column suggest that a certain amount of carving was undertaken on the ground before the blocks were assembled. The Column contains an interior staircase that gives access to the platform at the top (fig. 4). Each drum comprising the Column shaft (including base and capital) is a monolithic piece of Luna marble with the stairs hollowed out probably before the block was lifted into place.[21] Carving the stairway into the drums of the shaft while they were on the ground would have reduced their weight by a maximum of 30% (1.75–4.00 tons per block), which would have been an advantage in lifting them. Aligning the previously carved treads between one block and another would have required a high degree of precision, and establishing a perfectly level surface between the blocks would also have been critical since cumulative error in the horizontal surfaces would have affected the verticality of the Column.[22] Moreover, the Column is built with entasis, which is a subtle tapering curvature over the length of the shaft. A. Claridge notes that the precision in the execution of the entasis, which can be measured at the outside edges of the windows lighting the stairwell, suggests that the edges along the joints of each drum were carved to the appropriate diameter while on the ground. The final curving surface between these drafted edges then would have been carved from top to bottom once the blocks were all in place.[23] The coordination both of the stair treads and horizontal surfaces between adjacent blocks and of the change in diameters due to the entasis would have required a certain amount of checking back and forth from block to block and presumably would have been carried out fairly close to the building site of the Column itself. Given the location of the brick ribbing in the north portico, the most likely location for such a work site would have been somewhere to the north of the Column courtyard.

The topography of the area north of the Column

[19] Modern concrete made with Portland cement acquires a majority of its expected strength after 28 days, but it continues to gain strength for many years. Roman concrete made with pozzolana/lime mortar would have acquired strength somewhat more slowly. The Roman builders were probably aware that concrete had to cure for a period. For example, in describing how harbor works should be constructed, Vitr. *De arch.* 5.12.3–4 recommends that if the concrete cannot be poured directly into a cofferdam, a block of concrete should be made and allowed to dry for two months before it is lowered into the water. This would imply that the Romans were aware of the necessary curing period.

[20] M. Wilson Jones, "One Hundred Feet and a Spiral Stair: the Problem of Designing Trajan's Column," *JRA* 6 (1993) 34–35 has already noted that access to the Column courtyard may have been possible only from the north.

[21] P. Rockwell, "Preliminary Study of the Carving Techniques on the Column of Trajan," in P. Pensabene ed., *Marmi Antichi* (*StMisc* 26 [1981–83]) 105; G. Martines, "La struttura della Colonna Traiana: un'esercitazione di meccanica alessandrina," *Prospettiva* 32 (1983) 62.

[22] Whatever method was used to establish level surfaces on the blocks of the Column, it would have presumably required heavy lifting equipment for maneuvering the blocks. Evidence for a method of leveling used in fifth-century B.C. Greece is attested at the Older Parthenon on the Acropolis in Athens (destroyed 480 B.C.). Fragments of large surface plates (2 m dia.; 500–600 kg) were used to establish smooth and level surfaces between adjacent column drums. On the surface of some fragments, a thin coating of red paint was preserved. M. Korres, *From Pentelicon to the Parthenon* (Athens 1995) 108–109, figs. 31–32 argues that the painted plates were set on the flat, joint sides of the column drums so that once the plates were removed the areas of the drum with red paint could be ground smooth. The surface plates would have been made in pairs so that any irregularities were matched on adjacent blocks.

[23] Claridge (supra n. 14) 17.

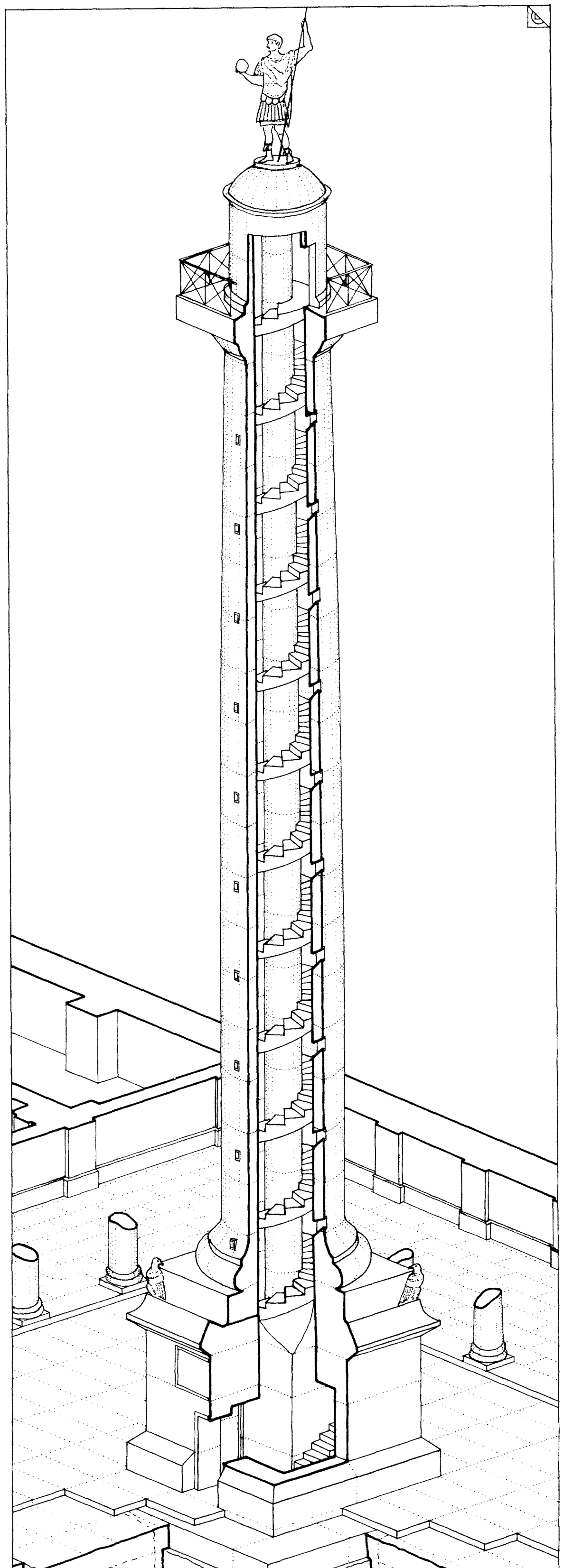

Fig. 4. Author's cutaway isonometric of Trajan's Column (shown without the decorative relief carvings). Scale 1:200.

is somewhat unclear. The known ancient buildings in the vicinity date to the second-third century A.D. and are later than the Trajanic complex (some of the remains are shown in fig. 1).[24] The land clearly sloped downwards towards the north, since the drains from the Column courtyard are channeled in this direction, and various structures excavated in this area lie at levels lower than the Column courtyard. Recent core samples taken under Palazzo Valentini indicate the presence of a concrete foundation level about two meters below the level of the Column courtyard paving at points 30–40 meters to the north of it.[25] In addition, other remains found about 13 m to the north of the Column courtyard are located at about the same level.[26] Meneghini argues on the basis of orientation and construction technique that these are not pre-Trajanic structures and that in the second century the area was divided into a series of descending terraces;[27] however, the precise nature of this area as well as the form of the proposed Temple of Divine Trajan remain controversial,[28] and none of the evidence found thus far provides an indication of the topography of the area before or during the construction of the Column. I assume, therefore, that the builders could have had access to at least 13 meters of relatively level land to the north of the Column courtyard for the work site.

LIFTING THE BLOCKS OF THE COLUMN

Once a block was carved and moved from the work site into the Column courtyard, the next challenge was to lift it into place. Of the blocks making up the Column shaft (not including the pedestal), the base is the heaviest at 55 tons.[29] The next heaviest is the capital at 53.3 tons, which also had to be lifted a great distance, ca. 34 m. As M. Wilson Jones points out in his discussion of the design of the Column, ancient builders were accustomed to handling larger weights, such as monolithic columns and obelisks, but these were rarely lifted clear of the ground as were the blocks of Trajan's Column.[30] Similar feats, however, had been accomplished: the corner cornice blocks of the Temple of Jupiter at Baalbek (first-second century A.D.),[31] which weighed ca. 108 tons,[32] were lifted to a height of 19 m from the floor of the cella and put into place.[33]

The best known type of lifting device from the Roman world is that described by Vitruvius and depicted on a late first century A.D. relief from the tomb of the Haterii (fig. 5).[34] It consists of two masts joined at the top and fitted with a three-pulley block attached to a rope leading to a windlass operated by men in a treadmill. A series of other ropes attached to two-pulley blocks controlled the lateral movement of the masts. The weight of a stone to be lifted was limited primarily by the strength of the ropes and pulleys and by the ability to apply the requisite amount of force, whereas the height was limited by the wooden masts of the lifting structure and perhaps by the length of the ropes. In his book on Roman bridges, the engineer C. O'Connor calculates that the Haterii type crane could have had a maximum height of between 15 and 18 m and could have lifted a 6.2-ton block about 13 m off the ground using at least one three-pulley block and a 1-m diameter windlass powered by five men in a 6-m diameter treadmill.[35] This is only about one-ninth the weight of the heaviest block of the Column shaft (base block at 55 tons) and one-third the height of the Column (38.4 m including the pedestal and statue base). The Haterii type crane clearly would have been inadequate for lifting very large blocks to great heights at Trajan's Column.

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[24] Meneghini (supra n. 7) 53–59, fig. 29.

[25] Meneghini (supra n. 7) 69–78, fig. 29: SA and S3.

[26] Meneghini (supra n. 7) fig. 29: PV1.

[27] Meneghini (supra n. 7) 69, 74–78.

[28] R. Meneghini, "L'architettura del Foro di Traiano attraverso i ritrovamenti archeologici più recenti," *RM* 105 (1998) 127–48 proposes two new, alternative locations for the Temple of Divine Trajan.

[29] I have calculated the weights of the blocks based on a weight of 2750 kg/m^3 for the marble and on the measurements of the Column in Wilson Jones (supra n. 20) fig. 3.

[30] Wilson Jones (supra n. 20) 33–36, (supra n. 1) ch. 8 argues that the weight of such large blocks would have affected even the design and layout of the Column itself.

[31] The temple was begun during the Augustan period, and a graffito dated to A.D. 60 at the top of one of the column drums gives a *terminus post quem* for the entablature blocks: N. Jidejian, *Baalbek: Heliopolis "City of the Sun"* (Beirut 1975) 23.

[32] For a list of some of the heaviest known blocks lifted in antiquity, see J.J. Coulton, "Lifting in Early Greek Architecture," *JHS* 94 (1974) 17–19.

[33] T. Wiegand, *Baalbek: Ergebnisse der Ausgrabungen und Untersuchungen in den Jahren 1989 bis 1905* (Berlin 1921) pl. 22.

[34] Vitr. *De arch.* 10.2.1–2. Bibliography for Haterii relief: O'Connor, *Roman Bridges* (Cambridge 1993) 49–50; J.-P. Adam (A. Mathews trans.), *Roman Building: Materials and Techniques* (London 1994) 46–47, figs. 94–95.

[35] C. O'Connor (supra n. 34) 49. Cf., a German team reconstructed a crane like that shown on the Haterii relief; it was 10.4 m high and could lift a maximum of five tons: W. Meighörner-Schardt, "Zur Rekonstruktion eines römischen Bockkranes," *Journal of Roman Military Studies* 1 (1990) 59.

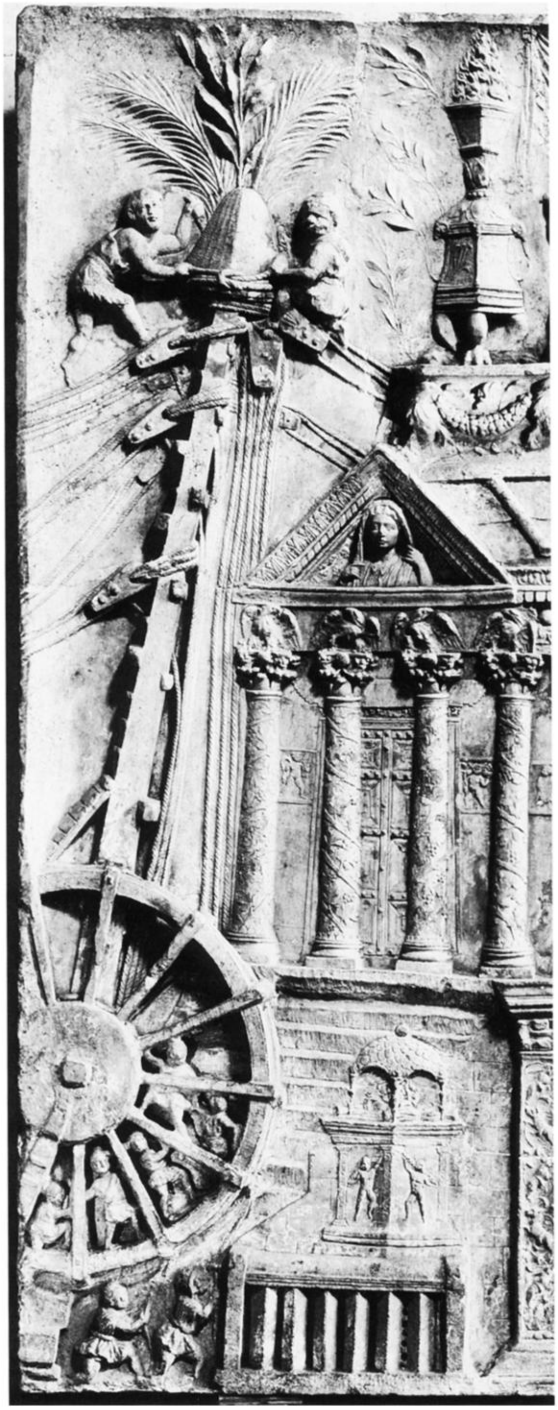

Fig. 5. Crane and treadmill depicted on a marble relief from the tomb of the Haterii on the *via Labicana* (late first century A.D.) (Courtesy Alinari/Art Resource, NY). The three pulley blocks to the left of the mast and one to the right are connected to ropes for maneuvering the mast back and forth and show only two pulleys in each block, whereas the pulley block to the right that is attached to the object being lifted (not shown) has three pulleys, one above the other.

Hero of Alexandria, who was writing in the first-second century A.D.,[36] cites lifting devices consisting of one, two (i.e., the Haterii type), three, and four masts and notes that the four-mast type was used for the heaviest loads.[37] He describes how such a tower should be built:

> As for the engine that has four masts, it is made for the very great weights, and it is like this: four wooden posts are set up so that their arrangement is like the shape of a quadrangle with parallel sides, and in width it should be such that there is room to move the stone inside it and to lift it easily. Then we fasten to the ends of these posts balks going from one to another, and this should be done skillfully and solidly. Then we arrange on these beams other beams and fasten them to each other with a fastening in a different arrangement, so that all the posts are joined together. Then we fasten the pulleys in the middle of these beams in the point where the balks come together. Then we make fast the stone in the rope that is over the pulleys, and we pull it, and the burden is lifted. It is necessary in all mechanical engines that we guard against using nails or pegs; in short, whenever it is a question of weight, and especially of great weight, on the contrary we have to use ropes and cords and fasten by them what we want instead of the thing that we want to put nails into.[38]

The surviving manuscripts of the *Mechanica* consist of Arabic translations of the original Greek texts. Diagrams, which may reflect those on the original drawings, accompany some of the manuscripts.[39] The diagram illustrating the four-mast lifting tower shows the pulley attached to the intersection of diagonal cross pieces attached to the top of the four vertical masts (fig. 6). If we assume that the builders of Trajan's Column used some type of lifting tower as opposed to a crane, diagonal beams similar to those described by Hero would have had to span ca. 10 m. Calculations of bending stresses show that a point load of up to 55 tons at the center would have been far beyond the capability of any imaginable beam of this length. The weights of the blocks of the Column

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[36] Hero's dates have been somewhat controversial, but most scholars generally agree now that he was active during the second half of the first and the early second centuries A.D.: A.G. Drachmann, "Heron and Ptolemaios," *Centaurus* 1 (1950) 117–31; G. Argoud, "Héron d'Alexandrie: mathématicien et inventeur," in G. Argoud ed., *Science et vie intellectuelle à Alexandrie* (Saint Étienne 1994) 53–65.

[37] Hero *Mechanica* 3.2–5; A.G. Drachmann, *The Mechanical Technology of Greek and Roman Antiquity: A Study of the Literary Sources* (Madison 1963) 97–102.

[38] Hero *Mechanica* 3.5 (trans. Drachmann [supra n. 37] 101–102).

[39] Drachmann (supra n. 37) 19–21.

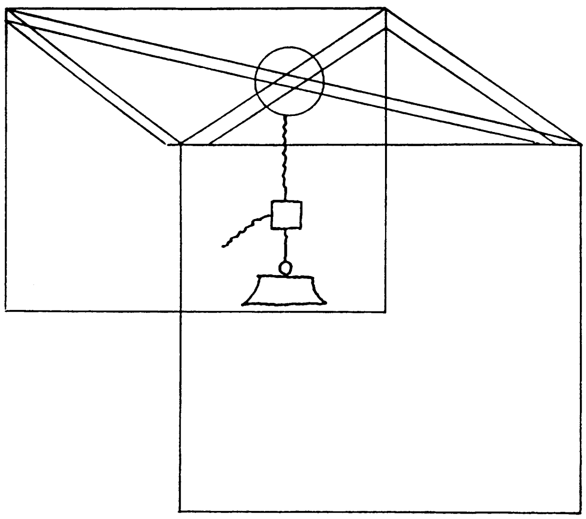

Fig. 6. Drawing of sketch accompanying the Arabic manuscript (Leiden) of Hero's *Mechanica* showing a four-mast lifting tower. (From A.G. Drachmann, *The Mechanical Technology of Greek and Roman Antiquity: A Study of the Literary Sources* [Madison 1963] fig. 38)

are extraordinary, and modifications to standard methods were probably made to compensate. In the following discussions, I use Hero's four-mast lifting tower as a basic model for reconstructing a hypothetical lifting tower for the blocks of Trajan's Column, but I modify the details to account for the extraordinary loads.

Other literary sources offer some evidence to aid in reconstructing the lifting tower. For instance, the detailed joinery used may have been influenced by the military technology used to build siege towers. Apollodorus of Damascus, who designed Trajan's Forum (and in this capacity was perhaps also the person in charge of erecting Trajan's Column), wrote a treatise under Hadrian describing how to build siege machinery.[40] The treatise consisted of a text describing a series of illustrations comprising plans, elevations, and perspective views of various types of war machines, including siege towers. The original drawings are lost, but the texts have survived through Byzantine copies. Many of the joints described consist of composite constructions in which the members are sandwiched together and secured by a series of transverse braces nailed along the length of the member.[41] Siege towers were used in the Hellenistic period, and Vitruvius describes one 120 cubits high (53 m) by 23.5 cubits wide (10.4 m) at the base,[42] which is comparable in size to that of the structure required to build the Column. Given the military themes of Trajan's Forum, an adaptation of the technology used to build siege machines would have been appropriate. In the ancient world, as today, the most advanced civilian technology was often developed in military contexts.

Another useful model for reconstructing a lifting tower is the structure built by Domenico Fontana in 1586 to lift and then lower the Vatican obelisk before moving it to its present location in front of St. Peter's basilica (fig. 7). The materials, devices, and methods he used are all ones that existed by the second century A.D. and would have been available to the Roman builders: blocks and tackles, capstans, stout ropes, trusses, and composite joinery. Fontana's tower is meticulously documented in both texts and visual representations,[43] so we know the actual size and arrangement of the components used. Since the weight of the obelisk (361 tons)[44] was far greater than that of any of the blocks of Trajan's Column, the basic mechanisms used to raise and then to lower it should be more than adequate for lifting the blocks of the Column.

RECONSTRUCTING THE LIFTING TOWER AND WORK SITE

The design of the hypothetical lifting tower presented here (figs. 8 and 9) is the result of an attempt to understand better the complexities of lifting the

[40] R. Schneider, *Griechische Poliorketiker* (Berlin 1908).

[41] Apollod. *Poliorketiker* 155.7–13; Schneider (supra n. 40) 22. O. Lendle, *Schildkröten. Antike Kriegsmaschinen in Poliorketischen Texten* (Wiesbaden 1975) 111–21, figs. 48–50. Hero *Mechanica* 3.5 advises that members should be connected using ropes rather than nails, but he does not discuss the creation of composite members. Both techniques could have been used depending on the application. The use of nails and cross pieces to create the composite vertical masts of scaffolding was still employed in Italy during the 19th and early 20th centuries.

[42] Vitr. *De arch.* 10.13.5. L. Callebat and P. Fleury, *Vitruve: De l'architecture, livre X* (Paris 1986) 245 express doubts as to whether a structure of such large dimensions was actually used.

[43] The principle primary source is D. Fontana, *Della trasportazione dell'obelisco vaticano* (Rome 1590). For a commentary on the process by which the Vatican obelisk was lowered and reerected as well as on the tools and materials, see W.B. Parsons, *Engineers and Engineering in the Renaissance*[2] (Cambridge, Mass. 1968) 158–67.

[44] B. Dibner, *Moving the Obelisks* (Norwalk 1950) 59. Fontana calculated that the obelisk weighed 963,537 35/48 *libbre* (327 tons): Fontana (supra n. 43) 10; Parsons (supra n. 43) 160.

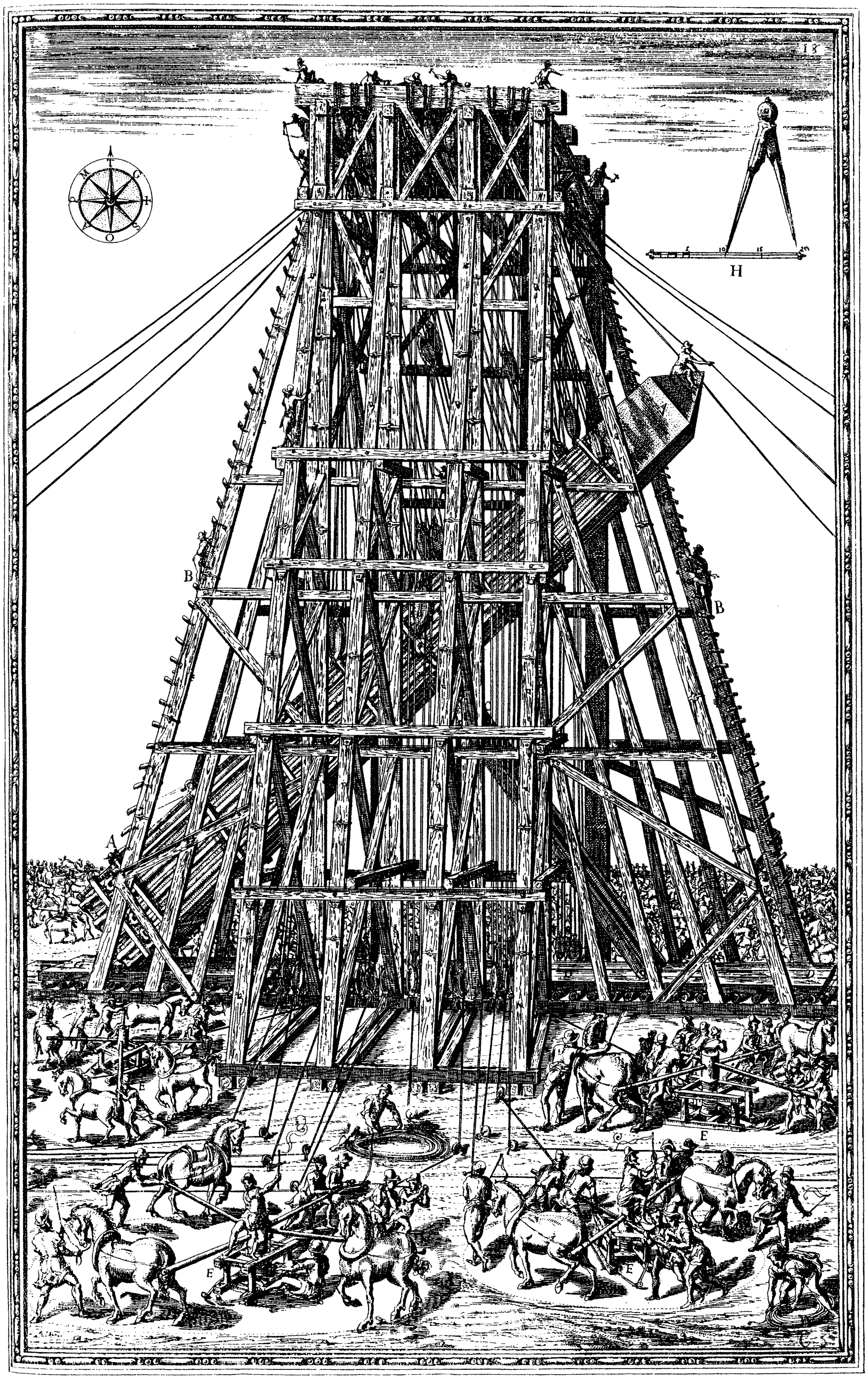

Fig. 7. Engraving showing the tower and work site of Domenico Fontana's project to lower the Vatican obelisk before moving it to its present location. (From D. Fontana, *Della trasportazione dell'obelisco vaticano* [Rome 1590] 18)

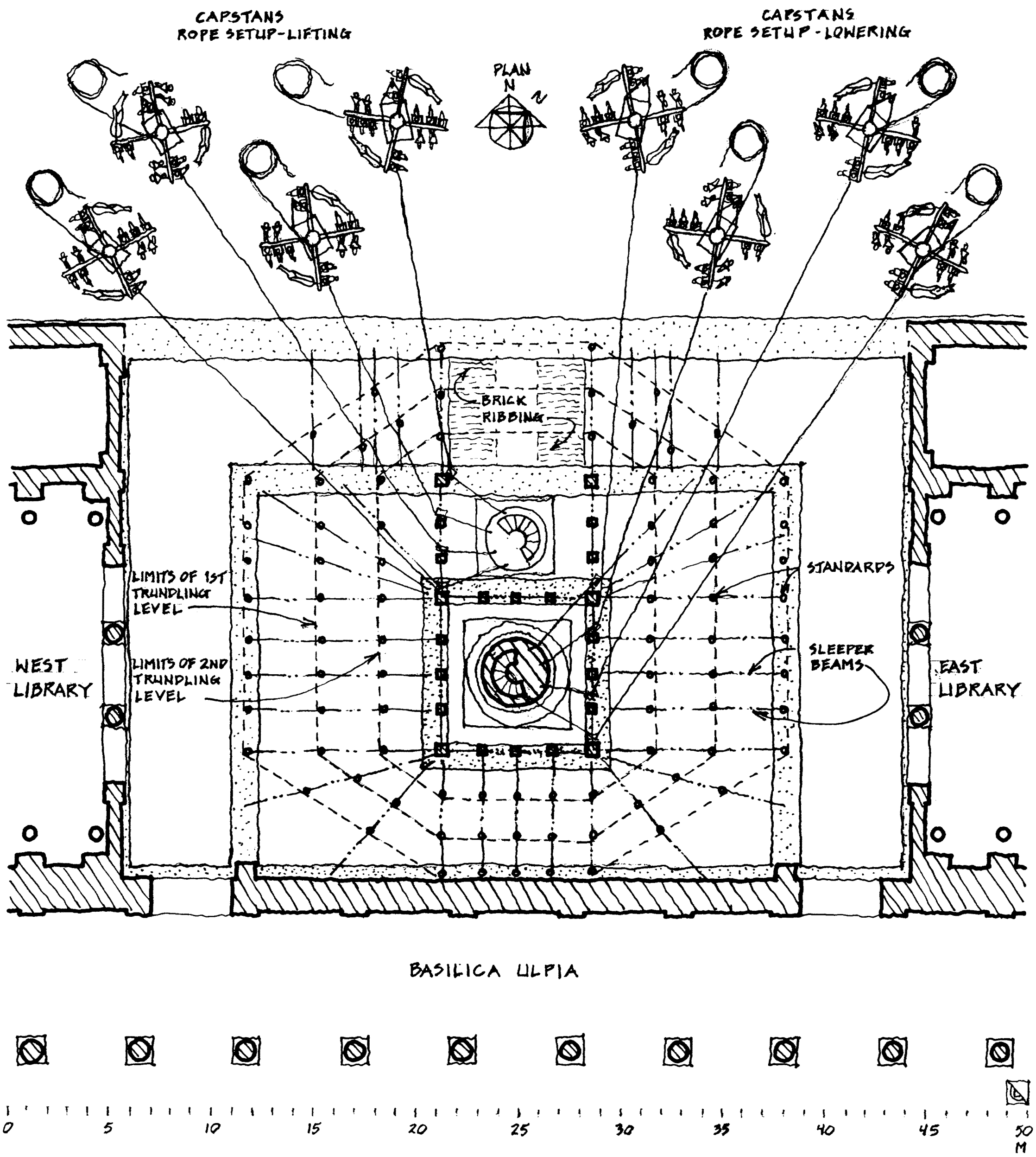

Fig. 8. Author's sketch plan of Column courtyard showing hypothetical arrangement of lifting tower, bracing/scaffolding, and capstans. The drawing is divided in half and shows two different schemes for rope setup: lifting to the left and lowering to the right. The left hand group of capstans is attached by ropes to the lifting shaft (with a block waiting to be lifted), while the right hand group is shown similarly attached to the lowering shaft (where the Column is being built). The lewis irons for attaching the pulleys to the block (as shown in fig. 11) would have been located between the dowel holes on the two diagonal axes and the windows on the two main axes. Sleeper beams span between foundations to provide support at ground level for the standards of the bracing and to protect the setting bed for the paving.

large marble drums comprising the shaft of Trajan's Column. The blocks of the pedestal are the largest and heaviest (ca. 77 tons) of the Column, but they did not have to be lifted to extreme heights as did the drums of the shaft. Since the pedestal blocks are not centered under the shaft drums, they may well have been lifted using a different mechanism that was disassembled before the lifting tower was erected, and I do not deal with them in the following discussion. In describing the proposed reconstruction for the lifting tower, I focus on the issues and problems that would have confronted the ancient builders and

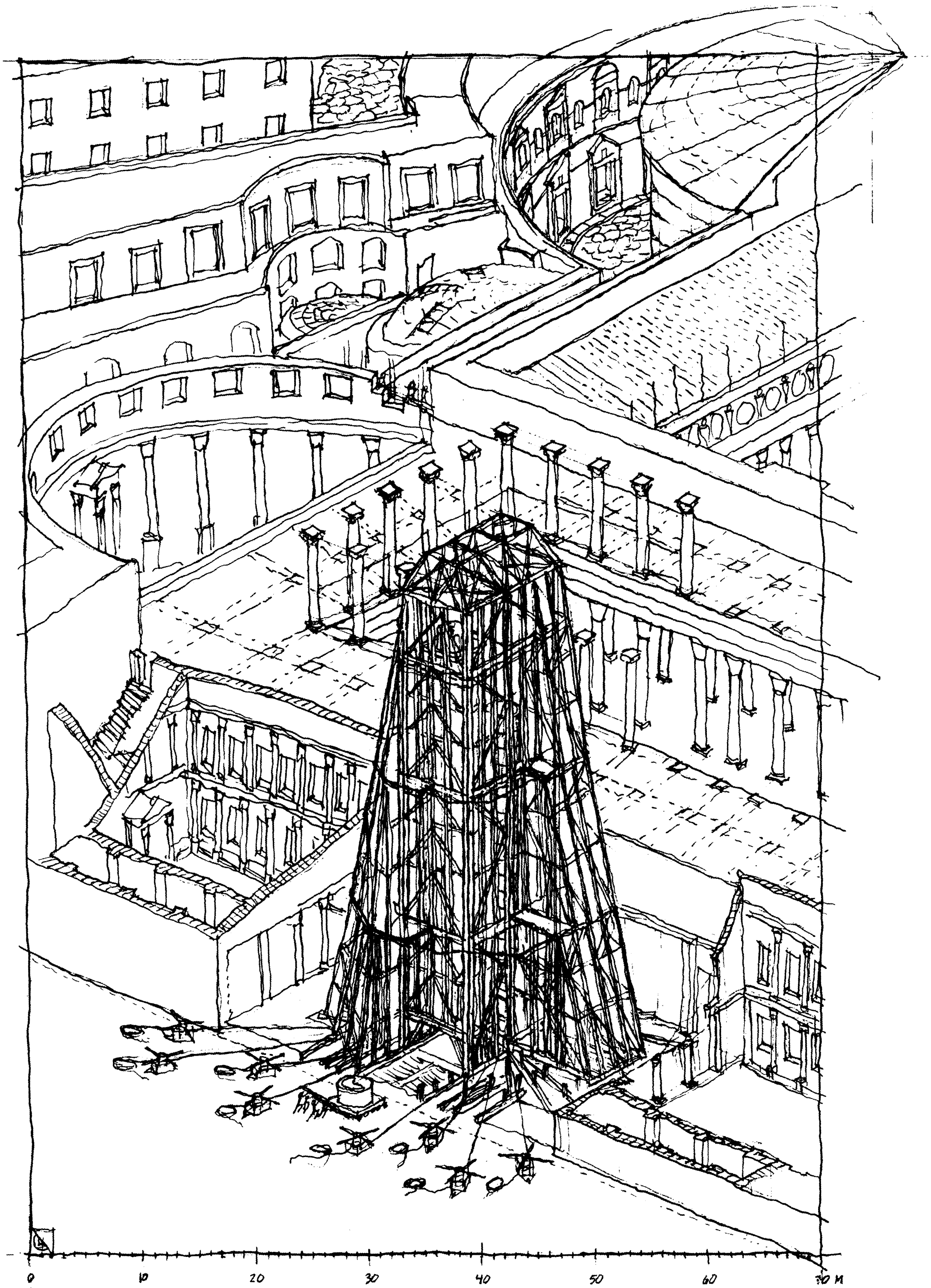

Fig. 9. Author's sketch of hypothetical tower used to put the blocks of Trajan's Column in place. The partially constructed Basilica Ulpia as well as Trajan's Forum and Markets are in the background. The Column is being erected within the lowering shaft as the next block is about to be maneuvered over the bipedalis reinforcing of the north portico substructure before being placed in the lifting shaft. The front corner of the scaffolding is shown cutaway to reveal the lifting shaft. Trundling floors are shown at points one-third and two-thirds the way up the tower.

provide possible solutions to these problems, but as ever in the study of ancient structures for which there is little direct evidence, the value of the exercise lies in the process of reconstructing rather than the final reconstruction.

Superstructure and Foundations

As cited above, Hero recommends a four-post wooden structure for lifting very heavy objects, but no writer ever describes how an object was moved horizontally after it was lifted. Since the marble blocks of the Column had to be lifted up, transferred horizontally, and then lowered into place, the most likely solution is that the structure consisted of two parts: a lifting shaft and a lowering shaft, essentially two towers put together next to each other. In this case, some sort of trundling floor was probably erected to enable the transfer of the block from the lifting shaft to the lowering shaft.

The weight of the structure itself would have been substantial. During the lifting process, it had to transfer the weight of the block to the ground and would have needed foundation support. The foundation of the Column projects from the pedestal ca. 1.45 m on all four sides and is capped with 77-cm thick slabs of travertine (figs. 2:F and 10).[45] This travertine platform together with the foundation wall of the colonnade of the north portico would have provided a stable base for the corner posts of the two shafts (fig. 8).[46] Intermediate vertical posts would have been necessary to support the heavy beams of a trundling floor.[47] Those located between the Column foundation and the north portico foundation could have been supported on ground level sleeper beams. The intermediate posts on the north side of the lifting shaft could not have extended down to the ground since the opening at the base had to be kept clear for the blocks to enter, so oblique bracing members are shown transferring the loads of the intermediate posts to the corner posts at ground level (fig. 9).

Fig. 10. Photo of lower portion of Trajan's Column. Travertine foundation cap is visible at base of pedestal. Arrow indicates the joint between two blocks with a robber hole where a connecting dowel has been removed.

Trusses

The structure topping both the lifting and lowering shafts had to support the pulley blocks to which

[45] The travertine slabs have numerous holes cut into the upper surface. Some of the smaller ones are for clamps; others are for the levers used to maneuver the blocks into place. At three of the four corners of the pedestal (two on the south side and one on the north side) there are larger holes (50 × 20–22 × 10 cm deep) that could relate to a more substantial structure (fig. 2:F). The remains of the iron clamps (3 cm thick × 4 cm wide) and lead that were cut when the two southern holes were carved show that the holes were made after the slabs were put in place and clamped together, but whether or not these holes were cut by the Trajanic builders or by later builders is unclear.

[46] Using Fontana's model, I have shown vertical corner posts for the tower. An alternative solution would be to have the corner posts leaning slightly inwards as in the siege tower described by Vitruvius. This would have complicated the joinery and construction of the tower, but it would have also offered the structural advantage of reducing the span of the trusses at the top.

[47] Calculations of beam stresses in an oak timber supporting a load of 59 tons (i.e., block and sledge) at three points show that a beam 37 cm wide and 50 cm high would need to be supported about every two meters; therefore, I show three intermediate posts for the lowering shaft and two for the east and west side of the lifting shaft, which have a smaller span. Similar sized ancient beams: the 49.5 cm high × 38.5 cm wide fir tie beams used in the fourth-century A.D. truss of St. Paul's Outside the Walls: Adam (supra n. 34) 212; the 44 cm square fir beam used in Agrippa's Diribitorium: Plin. *HN* 16.202; and the 64.2 × 26.4 cm tie beams of the East Colonnade of Trajan's Forum: J.E. Packer, *The Forum of Trajan in Rome. A Study of the Monuments* (Berkeley 1997) 427.

the ropes were attached. The pulleys would have been located directly above the connections to the marble drum so that the ropes ran vertically (fig. 11). If, on the other hand, the pulleys were attached to the outer structure of the tower, the ropes would have become increasingly oblique as the drum approached the pulleys. Since the intermediate posts on the east and the west sides of the lifting shaft had no foundation support, the load exerted on the pulleys had to be transferred to the corner posts. Given the large span (6.75 m) between the corner posts, some form of trussed structure would have been necessary.[48] A series of parallel trusses, such as those used in Fontana's lifting tower (fig. 7), would not have been feasible for the lifting shaft since its intermediate posts lacked foundation support. I show instead a pyramidal trussed structure that would have transferred the loads to the corners. Little direct evidence exists for an ancient truss of this form, but complex radiating trusses must have existed and have been used to span the apses of the Basilica Ulpia (ca. 21 m radius) and the east and west exedrae of Trajan's Forum (ca. 19 m radius).

Bracing and Scaffolding

The tower would have needed lateral buttressing to counteract the horizontal thrusts from any wind pressures that developed in the upper part of the structure and to stabilize it during the lifts. Fontana used a series of inclined braces to shore the vertical masts of the Vatican lifting tower (fig. 7),[49] and similar shoring would have certainly been necessary for the lifting tower for the Column. The siege towers described by Vitruvius were also wider at the bottom than at the top.[50] Likewise, the lifting towers used this century to reerect the columns of the Basilica Ulpia were typically wider at the bottom.[51] Minimizing the mass at the top of the tower would have reduced the wind loads and lowered the center of gravity resulting in a more stable structure.

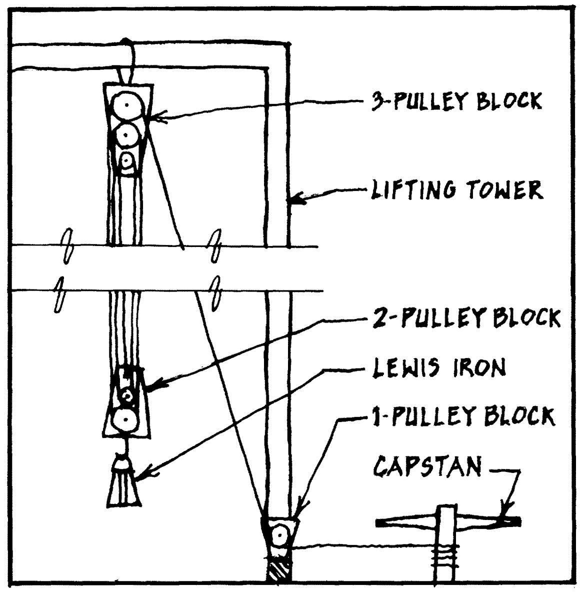

Fig. 11. Author's schematic diagram of the rope and pulley configuration for one of the eight proposed capstans of the lifting tower

The bracing could have also been used to support scaffolding for working the blocks once they were in place.

The bracing/scaffolding would have been made of lighter members than the tower itself, but it still had to support the live load of men and materials as well as its own weight, which once it reached as high as 40 m, would have been substantial. In order to distribute the weight and to protect the setting bed of the courtyard, sleeper beams could have spanned from foundation to foundation to support whatever configuration for the bracing was chosen (figs. 8 and 9). The travertine foundation cap of the north wall of the Basilica Ulpia has a 50-cm projecting ledge that probably supported a marble step at the base of the wall (fig. 2:G),[52] and this too could have been used to support sleeper beams before the revetment was added.

[48] Vitr. *De arch.* 4.2.1 describes what was probably a truss: P. Gros, *Vitruve: De l'architecture, livre IV* (Paris 1992) 93–96. Although no remains of trusses exist from the early Imperial period, the spans of some spaces such as the nave of the Basilica Ulpia (ca. 24 m) suggest that the principle was certainly known and applied: Packer (supra n. 47) 239–40; Adam (supra n. 34) 209–12.

[49] Fontana (supra n. 43) 11; Parsons (supra n. 43) 159.

[50] Vitr. *De arch.* 10.13.4. The height of the tower and bracing presented here (48.5 m) is somewhat less than that of the siege tower described by Vitruvius (53.0 m) whereas the width of the base of the structure is much larger (26.0 m as opposed to 10.4 m). The siege towers had to be mobile and therefore as light as possible without compromising stability. The lifting tower on the other hand was immobile, and the base could have been enlarged with no detrimental effect.

[51] Packer (supra n. 47) fig. 42.

[52] The ledge that projects out from the wall has dowel holes and pour channels for lead, indicating that a block of some sort was once anchored to it. Since some of the pour channels run up the vertical surface of the raised platform that supported the wall blocks, whatever was attached to the projecting ledge could not have been very tall and was probably a step.

Trundling Floors

Since the block had to be transferred horizontally once it was lifted, trundling floors would have been necessary to facilitate the move. Such floors had to be removable for the blocks to pass through but also substantial enough to support the weight of the block. The use of trundling floors at a few set heights would have eliminated the need to provide a new floor at the level of each block. For example, each of the lower six or seven blocks of the Column shaft could have been lifted to the same platform, moved horizontally and lowered into position. Then, when necessary, the next section of the tower could have been added and a new platform established. One can also imagine the tower and scaffolding being built in stages corresponding to the trundling floors rather than being built in their entirety before the lifting began.

Carts and Sledges

Moving such large blocks would have been accomplished with either carts or sledges. Hero of Alexandria notes that large blocks of stone were often moved on sledges rolled over thin round sticks, pulled over boards, or attached to wheels.[53] Fontana used a similar type of sledge with rollers to move the Vatican obelisk (fig. 7).[54] Carts pulled by draught animals may have been more appropriate for moving the blocks through the streets,[55] but sledges on rollers would have been more useful for moving the blocks into the lifting shaft since there was not room in the shaft for both cart and animals. Each of the blocks, therefore, would have been brought from the work site probably on a sledge and moved over the reinforced part of the portico vault into position at the base of the lifting shaft.

Ropes, Pulleys, and Capstans

Vitruvius describes a system of pulleys, ropes, and capstans used to lift heavy objects.[56] Fontana employed a similar system to lower the Vatican obelisk and then reerect it in its present location. In his calculations, Fontana estimates that each capstan powered by four horses and supplied with a 7.5-cm diameter hemp rope could lift 6.78 tons (20,000 *libbre*).[57] This figure roughly coincides with what O'Connor calculated (6.20 tons) as the lifting capacity of a five-man treadmill 6 m in diameter operating a 1-m diameter windlass. We know from illustrations on relief panels and from literary descriptions that Roman builders employed both the treadmill-powered windlass and the type of capstan used by Fontana.[58] The advantage of the treadmill is that a higher leverage ratio is possible than with a capstan, but the disadvantage is that fewer men (and no animals) could be used. The depictions of treadmills typically show them being used singly whereas a relief panel from the base of the obelisk of Theodosius at Constantinople (A.D. 390) shows a number of man-powered capstans being used together to raise the obelisk there. The pushing/pulling capacity given in various sources for a man and for different types of beasts varies greatly, making a reliable calculation difficult.[59] This is in part due to the variability in the coefficient of friction between the feet/hooves and the ground in different situations. In this reconstruction (figs. 8 and 9), I have chosen to illustrate capstans because they could have been controlled more precisely than windlasses powered by treadmills. As described below, the even application of force to all the ropes would have been a critical factor in the lifting process. Although Fontana calculated his rope capacity based on four horses, he lists an average of 3.5

[53] Hero *Mechanica* 3.1; Drachmann (supra n. 37) 95, fig. 34. Hero also indicates that the thin rollers are best used with lighter loads since the heavier loads tend to crush the sticks as the sledge moves along; rollers, however, have often been used in quarries for very heavy blocks and were used for the moving of the Vatican obelisk with no adverse effects.

[54] Fontana (supra n. 43) 20, 24.

[55] For the use of carts to transport heavy loads of marble, see D.P.S. Peacock and V.A. Maxfield, *Mons Claudianus: survey and excavation, 1987–1993* (Cairo 1997) 261–63.

[56] Vitr. *De arch.* 10.2.7.

[57] Fontana (supra n. 43) 7 (ropes), 10 (weight); Parsons (supra n. 43) 160. The calculations are based on 1 *libbra* = 0.339 kg: R.E. Zupko, *Italian Weights and Measures From the Middle Ages to the Nineteenth Century* (Philadelphia 1981) 130.

[58] Both types are described by Vitr. *De arch.* 10.2.7; Callebat and Fleury (supra n. 42) 98–99. The treadmill is shown on the Haterii relief (fig. 5) and a relief from Capua: Adam (supra n. 34) fig. 92. Capstans such as Fontana used are depicted on the base of the obelisk of Theodosius at Constantinople: D.M. Bailey, "Honorific columns, cranes, and the Tuna epitaph," in D.M. Bailey ed., *Archaeological Research in Roman Egypt* (*JRA* Supp. 19 [1996]) fig. 1; E. Iversen, *Obelisks in Exile* 2: *The Obelisks of Istanbul and England* (Copenhagen 1972) fig. 10. The use of multiple capstans is also described by Ammianus Marcellinus (17.4.15) in his account of the lifting of the obelisk in the Circus Maximus (now at the Lateran) under Constantius II (ca. A.D. 357).

[59] B. Cotterell and J. Kamminga, *Mechanics of Pre-Industrial Technology* (Cambridge 1990) 24, 41; O'Connor (supra n. 34) 48–49; Parsons (supra n. 43) 160.

horses and 20 men (not all of whom were actually applying force) for each capstan.[60] Illustrations of the event show a combination of men and horses, usually about 12–14 men and two horses per capstan, which is what I show here (fig. 8).[61]

The ropes used by Fontana were 7.5 cm in diameter (1/3 *palmo*) and were made of hemp grown in Foligno (near Perugia), which was considered the best quality.[62] Pliny the Elder notes that hemp was also commonly used for rope in his day and that the best quality hemp came from Alabanda in Caria, though he also mentions hemp grown at Rosea in the Sabine territory in Italy.[63] Hemp rope was evidently used in the Roman quarries at Mons Claudianus where it was listed on an ostracon with other materials needed at the quarry.[64] Remains of ancient papyrus rope 6.5 cm in diameter have been found in the limestone quarries at the Tura caves outside of Cairo in Egypt,[65] which suggests that ropes similar in size to those used by Fontana would have been feasible in second-century A.D. Rome. A hemp rope 7.5 cm in diameter would have a breaking load of 32 tons;[66] therefore, it could lift Fontana's calculated load of 6.78 tons with a safety factor of 4.7, which is somewhat less than the safety factor of 6.0 recommended for modern lifting ropes but is nevertheless feasible.[67]

If Roman ropes and capstans could attain a similar capacity to those used by Fontana, eight ropes and capstans would have been required to lift the 55-ton base block of the Column. Capstans must be anchored to the ground to withstand the horizontal pull generated from the ropes. Since the Column courtyard was paved with a setting bed before the construction of the Column and the three porticos were covered with concrete vaults, pounding anchor stakes into the ground as recommended by Vitruvius would have been impossible.[68] Given the Trajanic brick stamps found in the walls of the libraries, we must assume that some construction had begun by the time the Column was being built and that the areas to the east and west of the Column courtyard were also unavailable, having been covered with setting beds for the floors of the libraries.[69] The capstans, therefore, were probably set up to the north of the courtyard enclosure. The ropes, after having been wound through the blocks of pulleys, could have then been run through other pulleys attached to the base of the east and west sides of the tower and then horizontally out to the capstans (fig. 11). Careful placement of the capstans would have allowed them to remain in the same location for both lifting and lowering. To achieve this, the placement of the standards for the bracing had to be coordinated with the layout of the capstan ropes to provide a clear run for the ropes of both the lifting setup and the lowering setup, a difficult task and one that had to be well planned before construction began. Locating the capstans in the area to the north would have allowed them to be attached either to the tower for the final lift or to other smaller lifting structures used for maneuvering the blocks during the preliminary carving. The capstans could also have been rigged to aid in moving the sledge that carried the blocks to the base of the lifting tower.

The length of the ropes could have limited the number of pulleys in each block. The hoisting ropes used by Fontana were 223 m long (100 *canne*), though he had three guide ropes that were double that length.[70] For lifting the highest blocks of the Column using two-pulley blocks, the ropes would have been over 210 m long. Using a three-pulley block at the top of the tower (as shown on the Haterii crane) would have reduced the amount of force needed to lift the weight, but it would have required longer ropes (ca. 300 m long), which is what I show in figure 11.

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[60] Fontana (supra n. 43) 33.

[61] Fontana (supra n. 43) 15, 20. Horses were very prized animals, so in ancient Rome we might expect to find mules rather than horses used for the heavy labor of turning the capstans. For draught animals, see Peacock and Maxfield (supra n. 55) 263–64.

[62] Fontana (supra n. 43) 7; Parsons (supra n. 43) 160.

[63] Plin. *HN* 19.173–74.

[64] Peacock and Maxfield (supra n. 55) 196.

[65] A. Lucas, *Ancient Egyptian Materials and Industries*[3] (London 1948) 161 notes that the remains of the ropes have not been precisely dated. The quarries, however, were in use from the third millenium B.C. when they supplied the limestone for the pyramid of Cheops: Cotterell and Kamminga (supra n. 59) 225 n. 12.

[66] This figure is based on the minimum breaking load given for three-strand manila rope in *British Standard Specification for Ropes made from Manilla, Sisal, Hemp, Cotton, and Coir*-BS 2052 (London 1989), and on the assumption that manila rope is 20% stronger than hemp rope: O'Connor (supra n. 34) 48.

[67] A.G.H. Thatcher, *Scaffolding: Treatise on the Design and Erection of Scaffolds, Gantries and Stagings*[2] (London 1907) 77.

[68] Vitr. *De arch.* 10.2.3. The same method of anchoring the capstans is shown in illustrations of the raising of the Vatican obelisk (fig. 7).

[69] Though there is little evidence for when the setting beds for the floors of the libraries were laid, I adopt the worst case scenario for the purposes of this exercise.

[70] Fontana (supra n. 43) 7.

Another issue that the builders had to confront when using very long ropes was that the capstan drum could handle only a certain amount of rope before the diameter of multiple layers of rope became too great and began to reduce the ratio between drum diameter and arm diameter. Excessive rope buildup could also result in the rope slipping from one layer down to the next causing a sudden slackening. The illustrations of Fontana's capstans show men guiding the excess rope into a coil as it comes off the capstan. The relief on the base of the obelisk of Theodosius also shows very little rope accumulation on the capstan drums.[71] The Roman builders presumably would also have allowed the rope to wind onto the drum for a few turns to prevent slippage, and then it could have been wound off as fast as it was wound on.[72]

Connections: Dowels and Lewis Irons

Metal dowels placed along the diagonal axes of the Column attached one block to the next as shown by the robber holes left where the dowels were removed in the post-antique period (fig. 10). The typical means of applying metal dowels to column drums was for the dowels to be hammered or leaded into holes carved in the lower surface of the upper block.[73] The block with the projecting dowels was then lowered so that the dowels fit into larger holes on the upper surface of the lower block. The gaps were later filled with molten lead.[74] The use of the dowels as connectors meant the block could not simply have been slid into place without a sledge; it had to be lowered from above so that its dowels slipped into the holes of the block below. Such a process would have required a second lift for the sledge to be removed and the dowels to be positioned above the appropriate holes, so a second set of pulleys would have been necessary for the lowering shaft.

The block had to be lifted with connections from above so that the lower face could be settled into place without the interference of ropes or other attachments. This was probably accomplished by using a series of lewis irons,[75] which were used to lift other heavy blocks at the Forum of Trajan. A largely intact cornice block belonging to the entablature of the portico of the Column courtyard and weighing almost eight tons retains the single lewis hole used to lift it.[76] Similar evidence at the Temple of Jupiter at Baalbek suggests that this was about the maximum capacity for a single lewis iron in the Roman world.[77] The Baalbek architrave blocks, which weighed 55–60 tons, were lifted using eight lewis irons resulting in an allowance of 7.5 tons per lewis iron.[78] Each of these blocks weighs roughly the same as the heaviest block of the Column shaft (the base block). Using eight lewis irons for lifting the blocks of the Column results conveniently in one lewis iron at the end of each of the ropes of the eight proposed capstans.

Coordination of the Lift

The process of lifting a block would have required a great deal of coordination between the men and/or animals applying the force to the capstans. If the force was not applied evenly, excessive stress on a few ropes could have had devastating results. Fontana numbered the pulleys and the capstans so that if any one rope became too loose or too tight, its capstan could be isolated immediately and the situation remedied.[79] During both the lowering and the reerecting process of the Vatican obelisk, Fontana was so concerned that the ropes be evenly loaded that he issued orders to have all capstans stop after three turns so that the tension in the ropes could be tested. He even had a special tower on which to stand to oversee and direct the process.[80] The signal to begin turning was given by a trumpet; the signal to stop was given by a

[71] Bailey (supra n. 58) fig. 1.

[72] I am grateful to Jim Coulton for his comments on the problems of rope buildup on capstans.

[73] Hammering the dowels could be done from below while using lead to secure the dowels would have required turning the block upside down.

[74] Adam (supra n. 34) 56, fig. 131.

[75] For a description and illustration of a lewis iron, see Adam (supra n. 34) 48–49, figs. 102, 110. Hero *Mechanica* 3.8 describes how to make and use lewis irons, and he stresses the importance of using the best quality iron for them. He warns that using iron that is too soft could result in bending, whereas using iron that is too hard could result in breaking. Indeed, Fontana discovered that the iron fastening bands used during the lowering of the Vatican obelisk were much more likely to fail than were the rope fastenings: Fontana (supra n. 43) 14–15; Parsons (supra n. 43) 162.

[76] Packer (supra n. 47) cat. 157, pl. 102.1. The hole is 19.4 cm deep and 14.7 cm × 6.9 cm at the top.

[77] The similarity of the ratio of weight per lewis hole in the two examples from the Forum of Trajan and the Temple of Jupiter at Baalbek suggests that the ancient builders were calculating the weight of blocks in order to design the lifting apparatus. Complex calculations of volumes and areas were certainly made for estimating quantities of material as shown by various formulae given by Hero *Stereometrica* 2.33. Pliny the Elder (*HN* 36.67–68) also describes a situation in which the weight of stone is measured according to volume.

[78] The eight lewis holes, which are 28 cm deep and 9 cm wide at the top, remain in the upper surface of at least one of the blocks: Wiegand (supra n. 33) 66–67.

[79] Fontana (supra n. 43) 13.

[80] Fontana (supra n. 43) 32.

bell. The spectators watching the event were ordered not to speak or make any noise under the penalty of death, and police were used to enforce the orders. Complete silence was said to have been observed by the spectators.[81] Without electronic means of communication, silence during the lifting of the blocks of the Column would have been crucial in maintaining communication between those monitoring the ropes and pulleys at the top of the tower and those on the ground operating the capstans. Though we have no description of the lifting process at Trajan's Column, the drama of such an event is illustrated by the descriptions of Fontana's feat. These accounts also give an idea of the types of issues encountered by the ancient engineer, issues that are often forgotten or taken for granted in the mechanized modern age.

CONCLUSIONS

Building Trajan's Column was not an isolated event; the procurement and transport of materials for the project extended into the city and beyond, and they would have been critical factors in the planning of the whole process. Necessary materials such as good quality rope, timbers, lime, pozzolana, bricks, and travertine would have been brought in from the hinterland of Rome using the Tiber or Anio rivers whenever possible or in some cases from even further afield.[82] Once in the city, these materials had to be transported to the site through the streets of Rome, as Juvenal so colorfully describes:

> Here's the great trunk of fir-tree swaying along on its wagon, and look, another dray behind it, stacked high with pine-logs, a nodding threat over the heads of the crowd. If that axle snapped, and a cartload of marble avalanched down on them, what would be left of their bodies?[83]

Not all materials provided such excitement in the streets of Rome. In most cases, the bulk materials could, at a certain point, be divided into smaller parcels and transported easily by cart to the site. For the Column, however, the most challenging of the materials to transport from origin to site would have been the marble for the blocks making up the Column itself.

The blocks came from the Luna quarries located some 300 km north of Rome (modern Carrara) and were shipped down the Tyrrhenian coast to Portus where they were transferred onto riverboats for the voyage up the Tiber to Rome.[84] The most likely section of the river for unloading large blocks of marble would have been between the Marmorata district at the base of the Aventine and the Forum Boarium.[85] The blocks of the Column, which were in their rough state and even heavier than the lifted versions, then had to be maneuvered through the streets of Rome to the building site. The widths of the roads could have been a limiting factor in the route taken. Two-way roads were at least 14 feet (4.1 m) wide to allow two carts to pass.[86] Since the widest block of the Column was 4.9 m, the transport would probably have been limited to the larger two-way streets.[87]

During the move from river port to building site, the major obstacle encountered by the movers would have been the Capitoline. The route to the south of the hill would have led from the Forum Boarium down the *vicus Tuscus* straight into the Forum Romanum. The movers then would have had to negotiate their way through the imperial fora and into the Forum of Trajan only to find themselves on the wrong side of the Basilica Ulpia. On the other hand, a route along the north side of the Capitoline,

[81] Fontana (supra n. 43) 10, 13–14, 17; Parsons (supra n. 43) 161–62.

[82] J. DeLaine, *The Baths of Caracalla: A Study in the Design, Construction, and Economics of Large-Scale Building Projects in Imperial Rome* (*JRA* Supp. 25 [1997]) 85–101.

[83] Juv. 33.257–60 (trans. P. Green, Penguin Books, New York 1967).

[84] For transport of marble by sea and river, see M. Maischberger, *Marmor in Rom: Anlieferung, Lager- und Werkplätze in der Kaiserzeit* (Wiesbaden 1997) 25–31. For an insightful discussion of the technical issues involved in transporting large blocks from quarry to building site, see W.E. Wallace, *Michelangelo at San Lorenzo: The Genius as Entrepreneur* (Cambridge 1994) 43–62.

[85] That the route taken for transporting large blocks into the city typically ran through the Forum Boarium is supported by a comment by Pliny the Elder (*HN* 36.105–106), who in describing the resistance of the vaults of the Cloaca Maxima to the clash of the runoff from torrential rains with the back flow of water from the Tiber, also notes their resistance to the weight of heavy blocks transported on the streets above. Since the Cloaca Maxima emptied into the Tiber at the Forum Boarium, Pliny presumably had in mind this area for the transport of large blocks (fig. 12).

[86] R. Chevallier (N.H. Field trans.), *Roman Roads* (Berkeley 1976) 89; L. Quilici, "Evoluzione della tecnica stradale nell'Italia centrale," in L. Quilici and S. Quilici Gigli eds., *Tecnica stradale romana* (Rome 1992) 30–32.

[87] If the drums were transported on their sides, they would be only 1.5 m wide, and narrower roads could have been used, but the higher center of gravity could have made the load less stable. For a discussion of the archaeological evidence for the layout of the Trajanic river port facilities at the Forum Boarium, see A.M. Colini, "Il porto fluviale del Foro Boario a Roma," in J.H. D'Arms and E.C. Kopff eds., *The Seaborne Commerce of Ancient Rome: Studies in Archaeology and History* (*MAAR* 36 [1980]) 46–49.

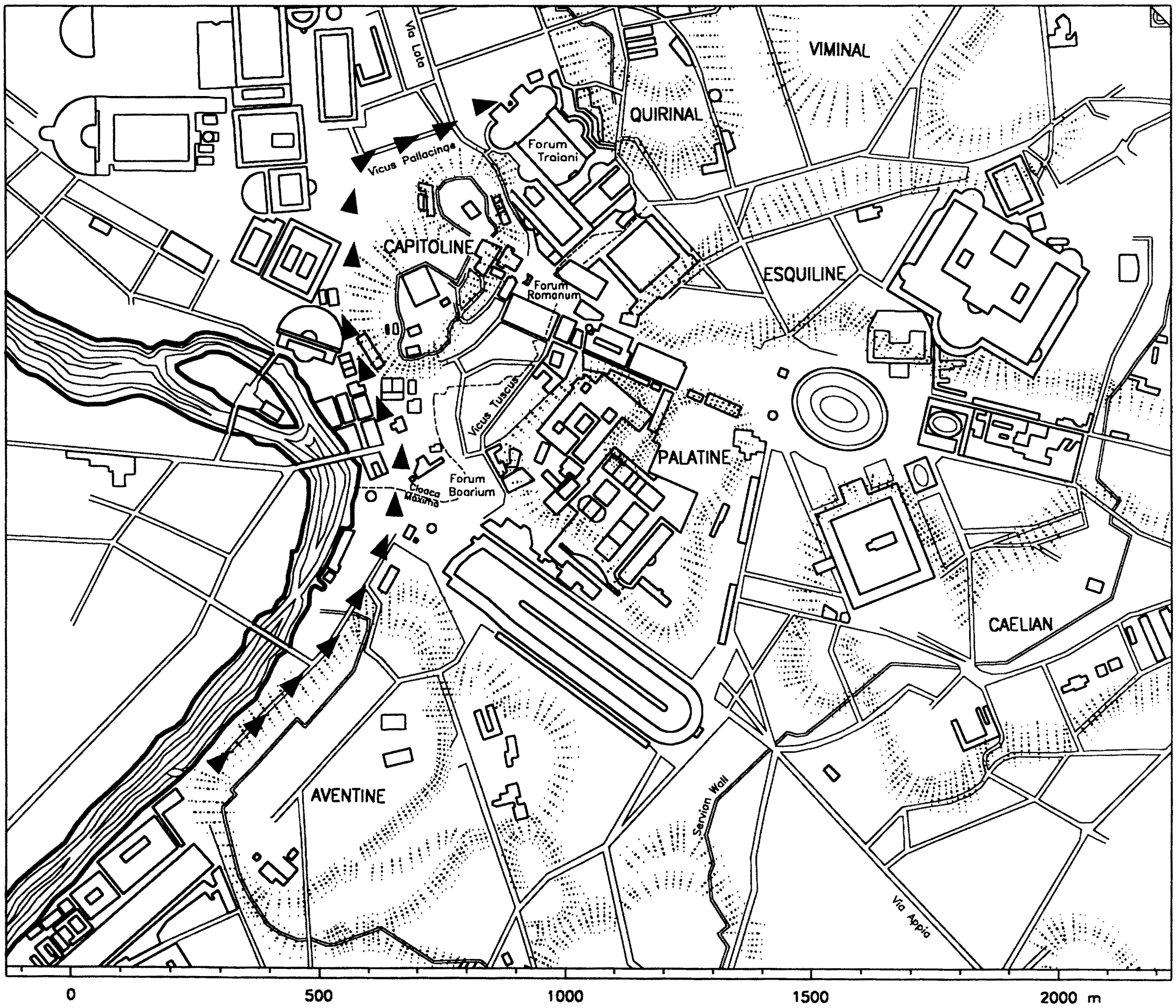

Fig. 12. Map of Rome showing most likely route for transporting the marble blocks for Trajan's Column from the Tiber river port to the building site. (Plan drawn using AcadR12 and based on Franciscus Scagnetti "Roma Urbis Imperatorum Aetate" [1979]). Scale 1:15000.

perhaps along the *vicus Pallacinae* (fig. 1),[88] would have led straight to the end of the *via Lata* and into the area north of the Column courtyard (fig. 12). Even if the blocks were unloaded farther up river,[89] the southern end of the via Lata would have been the most likely destination. Hence, the area north of the Column courtyard is the most obvious place for supplies and materials to muster.[90]

[88] The vicus Pallacinae is attested in a scholium of Cicero and can be located along the route of the present Via delle Botteghe Oscure and Via di S. Marco, which probably follows the route of the earlier Roman road: M. Marchetti, "Un manoscritto inedito riguardante la topografia di Roma," *BullCom* 42 (1914) 98–99; G. Gatti, "Saepta Julia e Porticus Aemilia nella Forma Severiana," *BullCom* 62 (1934) pl. 1.

[89] Maischberger (supra n. 84) 178 argues that the banks of the Tiber as far as the northern Campus Martius probably formed a continuous sequence of port structures.

[90] It should also be noted that workshops for marble decorative and architectural elements do not necessarily occur together with building sites. L. Haselberger, "Ein Giebelriss der Vorhalle des Pantheon die Werkrisse vor dem Augustusmausoleum," *RM* 101 (1994) 279–307 argues that the inscribed lines on the paving in front of the Mausoleum of Augustus relate to the Pantheon 800 m to the south. Also, two unfinished statues of Dacians probably intended for Trajan's Forum were found in the Campus Martius in Via del Governo Vecchio and in Via dei Coronari: Maischberger (supra n. 84), 119 no. 23, 121 no. 34, 157–58, 179. These examples, however, involve much smaller pieces of marble that were more easily transportable than the blocks of the Column.

If the materials for the entire Forum project (including travertine, bricks, lime, timbers, etc.) were typically coming from the north, the logical sequence of construction would have been to begin at the south end of Trajan's Forum and to work northwards. In fact, the existence of the Domitianic work at the Terrazza Domizianea and the Basilica Argentaria suggests that whatever plans Domitian once had for this area were also begun to the south and presumably would have stretched northwards had they been realized.[91] We know from the inscription on the pedestal of the Column and from the *Fasti Ostienses* that the Column was dedicated the year after the Basilica and Forum,[92] and this sequence makes sense from a logistical point of view. Since the Column is the northernmost monument of the Trajanic complex, it had to be built last so as not to block access to the rest of the site. Once the Basilica Ulpia was constructed, access to the Forum proper was limited on all sides. Likewise, as shown above, the equipment and manpower necessary to lift the individual blocks into place would have further impeded access to both the Forum and the Basilica from the north. The order of construction must have been carefully planned from the beginning so that access to the main area of construction at any one time was not blocked by the activity in another part of the complex. In addition, the use of brick ribbing to reinforce the vault of the Column courtyard portico substructure emphasizes the concern on the part of the builders for the damage to the site that could result from the maneuvering of the massive blocks that made up the Column. It also provides an indication of the sophisticated level of planning required in undertaking such a large project in the center of an urban area where mobility and access were limited.

The preparation of the site and the organization of manpower and materials are factors to be considered in the study of any construction project. As the building programs in the first and second centuries became larger both in scale and complexity, the builders had to deal with new types of organizational and logistical challenges. The construction of Trajan's Column was complicated by the limited space available as well as by the weight of the blocks and the height to which the upper ones had to be lifted. Far from being an "afterthought," the Column was the result of a carefully planned process. Building Trajan's Column should be seen as a *tour de force* of organizational and technological skill.

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[91] Supra n. 12.

[92] Supra n. 2.