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ONLINE SUPPLEMENTARY MATERIAL

Londinium's Landward Wall: Material Acquisition, Supply and Construction

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NOTE TO THE READER

The following online supplement supports the printed text of the main article. It presents material for two aspects of our study on Londinium's Landward Wall. Firstly, the detailed breakdown of the materials used and secondly, the methodological details of the energetics-based approach used to estimate the total cost of the Landward Wall. This approach uses a 'quantified time-labour equivalent',[1] measured in person-days, the results of which are presented in the main text.

MATERIAL FOR THE LANDWARD WALL

The tables given below provide the dimensions and volumetric details for the individual materials (Tables 1 and 2) and elements (Tables 3) of the Landward Wall. In addition, Table 4 presents the details of individual materials used in specific construction processes. The estimates provided are for the Landward Wall only, excluding the fort walls, which were previous structures incorporated into the city walls.[2] Equally, it is not possible to calculate the amount of time or quantities of material needed for the original gates, because too many details are unknown.[3] Consequently, the material volumes and labour figures related to the rubble course, facing stones, brick lacing courses, projecting chamfered plinths and coping stones were calculated for a solid wall. As this exercise is designed to identify the scale of production based on the minimum labour and material requirements of the Landward Wall, it has been assumed that the difference would not have been of a significant order of magnitude; however, the figures produced remain hypothetical. These measurements and details have been used to calculate the labour requirements for production, transport and construction that are detailed in the following sections and presented in the main text.

[1] Abrams and McCurdy 2019, 3.
[2] The west and north walls of the Cripplegate fort were thickened by the addition of a substantial internal wall so that their width matched that of the Landward Wall (Shepherd 2012, 24, 44, 53–56, 62–64, 78, 88–89, figs. 73, 74, 96–98, and Shepherd and Chettle 2012, 156–157); however there is no clear evidence connecting these interventions with the construction of the Landward Wall (Sankey and Stephenson 1991, 120). Consequently, the fort and its walls have been excluded from the volumetric and labour calculations.
[3] Maloney 1983, 98. Detailed information on the gates is only obtainable from Newgate, where foundations have been uncovered (Norman and Readers 1912, 294–295, plate LVI and Lyon 2007, 42–45). The evidence shows that the gate was most likely a double carriageway flanked by two towers. It is possible that Newgate was constructed prior to the Landward Wall, as Aldgate and Bishopsgate may have been (Hingley 2018, 177). The evidence for Bishopsgate, which has never been excavated, and Ludgate, which has been excavated recently (Rowsome 2014, 5), are equally unclear. As such, the gates have been excluded from the labour figures for material production and construction.

TABLES FOR THE MATERIALS USED IN THE LANDWARD WALL

TABLE 1: TOTAL VOLUME OF MATERIALS NEEDED FOR THE LANDWARD WALL

Material (Percentage of total wall)	Volume (m^3)	% of total
Kentish ragstone (Kent), 85 %	21,373	61.9
Carstone (East Kent), 2.5%	85.7	0.25
Weldon stone (Northamptonshire), <0.1%	0.3	<0.001
Barnack stone (North Cambridgeshire), 1%	33	0.1
Marquise Oolite (France), 1 %	557	1.6
Calcaire Grossier (France), <0.1%	55	0.15
Lydion brick (5% overall of which 4% brick-earth fabric)	1,934	5.6
Grog fabric (0.5%)	107	0.3
Eccles fabric (0.5%)	107	0.3
River pebbles (1%)	2,711	7.8
Mortar (5%)	7,594	22
Total	**34,557**	**100**

TABLE 2: DIMENSIONS FOR INDIVIDUAL MATERIALS OF THE LANDWARD WALL

Materials	Average Dimensions (Length x width x height)	Volume per unit (m^3)
Facing stones[4]	30 x 20 x 12 cm	0.007
Bricks[5]	43 x 29.5 x 4 cm	0.0051
Rubble	20 x 20 x 20 cm	0.008
Chamfered plinths[6]	43 x 29 x 14 cm	0.02
Coping stone, crenellation	175 x 60 x 40 cm	0.42

[4] Maloney (1983, 97) gives the height of the facing courses as 120–180 mm and the blocks of ragstone as ranging between 120 and 400 mm^2 x 180 mm. At Trinity Square, the Kentish ragstone blocks measured up to 450 mm wide by 150 mm high, but on average the blocks were 300 mm by 120 mm; Howell *et al.* (2015, 144). A width of 200 mm is recorded for facing blocks from the Wardrobe tower.

[5] This measurement is based on whole bricks recovered from Dukes Place and Trinity Place and is the equivalent of 1.5 x 1 Roman feet x 1.5 inches. At Dukes Place, the bricks ranged in thickness from 31.7 to 50.8 mm (Maloney 1979, 294; 1983, 100). At Trinity Place, the bricks, mostly red but with a few pale green/yellow examples, measured a maximum of 430 mm in length and 35–40 mm in thickness (Howell *et al.* 2015, 145). Each brick weighed *c.* 10 kg.

[6] Whipp (1980, 47) gives measurements of 500 mm long, 440 mm wide and 220 mm deep for the largest chamfered blocks from a section of the wall excavated in the area of the Wakefield Gardens, immediately north of the Tower of London. Maloney (1983, 98) gives measurements for the blocks as 310 mm long by 290–440 mm wide. At Trinity Square, the chamfered plinth blocks measure 450–750 mm long and 250 mm high; Howell *et al.* (2015, 144). However, we have based our average for the blocks on those from the Wardrobe Tower, Tower of London, where the chamfered plinths each measured 430 mm x 290 mm x 140 mm and weighed an estimated 46 kg each.

TABLE 3: DIMENSIONS AND VOLUMES FOR THE LANDWARD WALL

Element	Dimensions	Total Volume (m^3)
V-Shaped ditch	3.05–4.88 m wide, 1.17–2 m in depth[7]	2,459
Internal earthen bank	2 m high, 4–10 m in width[8]	12,750
Foundations	2.6 m wide, 0.88–1.17 m in depth[9]	15,606
Wall core, up to crenellation	2.05–2.63 m width,[10] 4–4.4 m high[11]	18,850
Brick, bonding courses[12]	Basal course, three bricks thick, three further courses, two bricks thick	2,148
Crenellation[13]	2 m high, 0.6 m in depth	2,065

[7] The v-shaped ditch has been identified at various points on the circuit of the wall (Merrifield 1965, 105; Maloney 1979, 295, 1980, 68, 1983, 101); however, evidence for the ditch on the western side of the circuit has yet to be found. It should be noted that calculations for the volume removed to create this ditch were produced based on a triangular prism and using average width and depth dimensions for the ditch. This should therefore be seen as an approximation of the material removed rather than an exact figure. Moreover, the calculations have been produced for a length of ditch only where there is archaeological evidence.

[8] Marsden 1970, 3–4; Maloney 1979, 295; Whipp 1980, 50. The bank is typically built up to a height of 2 m, tailing off *c.* 4–5 m away (*c.* 4.25 m at Cooper's Row (Merrifield 1965, 109, fig. 14), *c.* 4–7 m at Aldgate (Maloney 1979, 204; Chapman 1973, 10) and *c.* 5 m at King Edward Street and Central Criminal Court (Merrifield 1965, Gazetteer W52; Marsden 1970, 2–6)); however, on the eastern slope towards the Thames, the bank seems to have been 9 m or more in width (Whipp 1980, 50). The additional width in this area might relate to the presence of a wall turret discovered at the south end of the excavation. The original height could not be estimated due to modern disturbance, but it survives in places to a maximum height of 1 m. Trench V of the excavations carried out at the Tower of London and Tower Hill from 1954–1976 showed that the sloping surface of the bank was a maximum height of 1.5 m over a distance of 5 m (Parnell 1982, 94). If projected, this would have reached about 2 m in height against the face of the wall; however, further north the bank was recorded to a height of 1.9 m with widths of the internal bank recorded at *c.* 8.5 m (possibly with original measurements of 10 m; Parnell 1982, 94, 131). At the America Square (Site D) excavations, the bank was found to have consisted of sand, gravel and brickearth that had been banked up against the inside of the wall to a height of about 1.5 m (Hunt 2010, 55). The width of the internal bank was therefore considerably different depending on the area, and it is difficult to determine an average for the wall as a whole. As with the v-shaped ditch, we have calculated the volume of earth for the internal bank based on a triangular prism and using average width and depth dimensions for the internal bank (2 m high and 5 m wide), and this should therefore be seen as an approximation of the material needed rather than an exact figure.

[9] *RCHM* 1928, fig. 10

[10] *RCHM* 1928, 72.

[11] The original height of the wall is unknown, but sections survive to the level of the fourth brick-bonding course, 4–4.4 m above the plinth (Merrifield 1965, 105). This would probably have been at, or near, parapet level. At the southern end of the section of wall at 8–10 Cooper's Row (Site A), the Roman facing and core survive up to 4.3m above the plinth, up to the fourth tile course (Hunt 2010, 51–52).

[12] The three brick-thick basal bonding-course was offset by 70–80 mm from six courses of ragstone above it. The second bonding-course, two bricks thick, was offset by 60 mm from five courses of ragstone, above which the third bonding-course, two bricks thick, partially survives; Howell *et al.* 2015, 144.

[13] Maloney (1983, 101) estimates, based on comparison with the Roman wall at Canterbury (6.5 m), that the wall, including crenellation, stood at 6.4 m above the foundation with breastwork some 1.8–2 m high (including the coping stones). Coping stones indicate that the breastwork would have been 0.6 m thick (Merrifield 1965, 156).

TABLE 4: BREAKDOWN OF THE MATERIAL NEEDED
FOR THE LANDWARD WALL[14]

	Total pieces (per 1 m^2)	**Total pieces (per 1 m^3)**	**Total Volume (m^3)**	**Total number**
Aggregate (pebbles)[15]	–	–	2,374	–
Sand for mortar	–	–	4,744	–
Slake lime for mortar[16]	–	–	2,374	–
Pebbles for foundations[17]	–	–	884	–
Puddle clay for foundations	–	–	1,768	–
Rubble for foundation[18]	–	87.5	2,889	361,125
Mortar for foundation rubble	–	–	1,238	–
Chamfered plinth blocks	–	–	119	5,948
Rubble for core	–	87.5	13,159	1,649,375
Mortar for core	–	–	5,655	–
Facing (below crenellation)	25.5	–	3,446	478,590
Facing mortar, 5–10 mm joints	–	–	287	–
Bricks for bonding courses	–	–	2,148	421,176
Mortar for bonding courses	–	–	224	–
Facing for crenellation	–	126	1,879	260,972
Mortar for crenellation, 5 mm joints	–	–	190	–
Coping stones	–	–	612	1,457

[14] The materials for the production of mortar have been increased by 1.25 to allow for 25 per cent loss of volume on mixing; see DeLaine 2001, 247.
[15] In estimating the relative proportions of the materials used in making the mortar, the guidelines outlined in Vitruvius (II.v.5–9) have been used. The mortar in the wall is taken as a non-hydraulic mortar, comprising two parts sand, one part aggregate and one part lime. Water was also needed for mixing the mortar, about 15–20 per cent of the total volume. *Cf.* Pearson 2003.
[16] The volume of quicklime increases by 250 per cent on slaking: 2,374 / 2.5 = 950 m^3; see DeLaine 2001, 247.
[17] The foundations were composed of puddled clay (i.e. clay mixed with water) and pebbles; Maloney 1983, 98.
[18] At the top of the foundation trench is a footing, usually of two or three courses of concreted ragstone rubble; Maloney 1983, 98. At Dukes Place, the foundation trench was 1.15 m high; Maloney 1979, 294.

ENERGETICS-BASED APPROACH

The following section focuses on the assumptions underpinning the estimated quantity of labour and a discussion of the time-labour values adopted for the various work tasks necessary for the production of the materials used and the construction actions necessary to complete Londinium's Landward Wall. All the tables mentioned in the various sections below appear after the end of that section's text; however, the tables have been numbered consecutively.

ASSUMPTIONS

Our approach is based on architectural energetics, a now well-established methodology that seeks to quantify 'architectural remains in terms of the labour force involved in construction projects', in order to determine a total labour 'cost' for the overall project.[19] As in previous studies, estimating person-hours for building projects involves breaking down construction into its individual components and calculating each in terms of the building materials and labour required.[20] The labour requirements are determined for each process by assessing the time and likely minimum size of labour teams necessary for their completion. For the current analysis, only the quantity of materials and labour necessary for the construction of the stone and brick elements have been considered. Wood used for temporary constructions, such as centering and scaffolding, as well as in construction, such as wooded piles for the foundations, have been excluded.

The length of a working day has been adopted from Janet DeLaine,[21] who assumed 10 working hours (12 hours including breaks), the same as that assumed by Giovanni Pegoretti.[22] Andrew Pearson also assumed a 10-hour working day for his calculations on the construction of the Saxon Shore Forts,[23] while Elizabeth Shirley assumed a day of 8 working hours.[24] More recently, Seth Bernard has questioned the efficiency of pre-Industrial workers on the basis that the upwards of 6,000 calories consumed in an 8-hour working day by builders in the nineteenth and twentieth centuries who performed strenuous work would be unrealistic for the Roman period.[25] In its place, he proposed a working day based on the type of activity being undertaken, adopting a 5-hour day for arduous tasks and a 12-hour day for less intensive tasks. Moreover, we should also acknowledge that the use of military labour might allow for a different organisation of building works. In general terms, the Roman military were used to working long

[19] Abrams and McCurdy 2019, 3.
[20] The first person to establish the utility of this approach and set the methodology was Janet DeLaine in her seminal work on the Baths of Caracalla (DeLaine 1997). Her outline of the methodological approach remains the most detailed for the Roman period (DeLaine 1997, 105–106). See also DeLaine 2001.
[21] DeLaine 1997, 106.
[22] Pegoretti 1869 I, 13.
[23] Pearson 2003.
[24] Shirley 2000, 94.
[25] Bernard 2018, 78.

strenuous days,[26] and the Roman military did not have a fixed number of working hours;[27] in principle, this might have translated into longer working hours and/or a shift-based system of work.[28] While, therefore, this study has opted for the standard 10 hours of work per day, it is important to acknowledge that building projects which made use of military labour (and their schedules) might be potentially very different from the labour and time constraints typical of urban construction sites. Nonetheless, given the urban context of the project and the advantage of adopting the working hours typical of Roman energetics studies (making it easier to compare the end results), a 10-hour working day (12 hours including breaks) has been used in this study.

The number of working days in a season has proven more problematic. DeLaine, for example, used the graffiti from the Baths of Trajan[29] to calculate a construction season of 270 days over 9 months for outdoor work;[30] however, these figures are of course related to central Italy. For a Romano-British context, Peter Hill drew attention to climatic factors affecting construction in Britain.[31] He noted that in Britain work is normally carried out from the beginning of March to the end of October, and therefore he assumed a working season of 200 days.[32] This short working season is also used in the calculations for the Roman fort at Inchtuthil in Scotland[33] and for Saint-Bertrand-de-Comminges in south-west France,[34] while Martyn Allen suggested that the climate in Britain might allow only for a building season of April to October.[35] Considering London is located in the south-east of England, which usually has better weather conditions than Northumberland and Scotland, we have opted like Pearson for the higher rate of 270 days for outdoor work per construction season.[36]

One further constraint on the speed of construction is the maximum number of masons that can work alongside each other on a stretch of wall. DeLaine, for example, noted that the pattern of graffiti from the semi-circular exhedra of the Baths of Trajan implies a spacing of 3.5 metres.[37] Since the course of the Landward Wall is almost entirely straight, however, this paper

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[26] See Vegetius' fourth-century work, *Epitoma rei militaris*. His section dealing with the selection of recruits talks about the toughness of the Roman military: "No one, I imagine, can doubt that the peasants are the most fit to carry arms for they from their infancy have been exposed to all kinds of weather and have been brought up to the hardest labour. They are able to endure the greatest heat of the sun, are unacquainted with the use of baths, and are strangers to the other luxuries of life. They are simple, content with little, inured to all kinds of fatigue, and prepared in some measure for a military life by their continual employment in their country–work, in handling the spade, digging trenches and carrying burdens. In cases of necessity, however, they are sometimes obliged to make levies in the cities. And these men, as soon as enlisted, should be taught to work on entrenchments, to march in ranks, to carry heavy burdens, and to bear the sun and dust." (1.3).

[27] Plaut. *Capt.* 721–38 infers a working day corresponding to daylight hours.

[28] Liv. 5.19.11, noted that Camillus' soldiers worked in 6-hour shifts. Arguably, military units working in 6-hour shifts would have remained productive for their shift, as productivity would have dropped off sharply in the sixth hour of labour-intensive activity. On this point, Bernard 2018, 78.

[29] DeLaine 2015, 181. The sequence of dates painted on the walls of the Baths as work progressed suggests that there were no rest days and that builders worked from late February to October. For the graffiti from the Baths of Trajan, see Volpe 2010; Volpe and Rossi 2012.

[30] This figure of 270 days includes allowances for issues, such as poor weather in winter, and is higher than the 220-day average working year that DeLaine assumed in her study on the Baths of Caracalla (DeLaine 1997, 105).

[31] For example, the already complex large-scale production of brick might have been further complicated by the inclement weather of Britain and, unless planned carefully, could have caused bottlenecks in supply. See Snyder *et al.* 2017, for a discussion of some of these issues.

[32] Hill (2004, 293) noted that this figure matches the estimates of 200 working days per year with the weather in the area near the wall; on this see Bruce 1851, 94.

[33] Shirley 2000, 94–95.

[34] Esmonde Cleary and Wood 2006, 146–147. Although, they did note that the climate in the area of the Pyrenees is generally good from April to November, which would allow for a 244-day season, they opted for a more cautious figure of 200 days.

[35] Allen 2013, 102.

[36] Pearson 2003.

[37] DeLaine 2015, 181 and Volpe and Rossi 2012, 69–82.

has adopted the lower figure of 1.85 metres between workers suggested by the Renaissance architect, Filarete,[38] adopted by DeLaine in her earlier work on the Baths of Caracalla.[39] Moreover, we have assumed, as proposed by John Maloney,[40] that different gangs of builders worked on stretches of *c.* 25 metres in length, with each section completed to the full height of the wall. Finally, in accordance with DeLaine,[41] the figures below represent a rough estimate of the minimum labour requirements and should be seen to provide an idea of the scale of the project in terms of labour, rather than exact figures. Perhaps even more importantly, the figures should not be taken as an end in and of themselves but as a measure to examine wider questions about the Roman provincial building economy.

TRANSPORT CONSTANTS

Much of the material for Londinium's Landward Wall would have been brought via river and/or sea and then transported along the river Thames to be off-loaded at the Roman wharf (i.e. Regis House by London Bridge). For the calculations of river and sea transport, the Blackfriars 1-type vessel has been taken as the point of reference for carrying capacity and speed.[42] The shipwreck, dated to the late second century, contained 26 tonnes of Kentish ragstone. It is possible that the stone had been destined for the construction of the western side of the Landward Wall when it was wrecked near the mouth of the Fleet.[43] Gustav Milne and Simon Elliott both argued that the Blackfriars 1-type vessel was specific to the regional fleet of the *Classis Britannica*,[44] and therefore suggested the involvement of the *Classis Britannica* with the ragstone quarry industry (though it should be noted that there is little indication that the Blackfriars 1-type vessel was definitely military). Nonetheless, the Blackfriars 1-type vessel is highly suitable as the basis for our calculations.

For the rate of water travel, we have based our estimates on Elliott's recreation of the typical 254-km, four-day return journey for a load of stone in a Blackfriars 1-type vessel from its place of extraction at the upper Medway valley quarries to Londinium's Roman wharf.[45] To this we need to also allow time for loading and unloading in each turnaround (see below). Although in reality the time of year would have affected the amount of daylight per day, we have assumed a constant 10-hour day (12 hours with breaks) so that the total days per round trip and the total number of boat days needed for the transportation of each material could be calculated. For the other coastal and river transport routes (Carstone, Weldstone, Barnack, Marquise limestone, Calcaire Grossier and Eccles/Grog brick fabrics), we have taken the average speed of the Blackfriars 1-type vessel proposed by Elliott to estimate the overall return

[38] Spencer 1967, IV.23v.
[39] DeLaine 1997.
[40] Maloney 1983, 98, fig. 113.
[41] DeLaine 1997, 2001, 2015, 173.
[42] See Marsden (1994, 80–89) for the Blackfriars 1-type vessel. This data was combined with constants provided for river transport by Elliot (2016 and 2017), Pearson (2002) and Kendal (1996).
[43] Marsden 1994, 80–89, 91–95
[44] Milne 2000, 131 and Elliott 2017, 114, and Appendix B.
[45] Elliott 2016, 285ff, 2017, 115–116. This represents a two-day, 127-km journey each way. Elliott (2016, 285–305, esp. 298–305 and 2018, 98–100, fig. 46) based his calculation on a stone cargo with an 8-km journey (at 2 knots (3.7 km/h) and up to 3 hours) from Teston, East Farleigh, Tovil or Maidstone (where it was loaded onto the vessel) to the tidal reach of the Medway at Allington (or Snodland). After waiting for a falling tide, the vessel would journey 45 km (*c.* 6 hours and 4 knots (7.41 km/h)) up to Sheerness and then Morris' southern North Sea and Eastern Channel connectivity system. Elliot then allowed time for an overnight anchorage and an early tide so that the vessel could complete the 74-km journey (at 5 knots (9.26 km/h) and 8 hours) up the river Thames to Londinium.

journey times.[46] It is also worth noting that the shallow draft of the boat would have facilitated beaching on tidal shores for loading and unloading, something that may have been particularly useful for certain materials, such as in the collection of river pebbles.

In order to estimate the number of carts required, a maximum working day of 10 hours (12 hours with breaks) for animals on flat ground has also been assumed.[47] In addition, a cart with a capacity of 5 m^3 has been assumed, based on a relief from Langres in north-eastern France,[48] and a maximum weight of 500–1,000 kg has been presumed based on ethnographic evidence for a mule – or horse-drawn four-wheeled cart with 2 animals.[49]

Using these figures, we can examine, for example, the maximum number of bricks that can be moved per cartload. Based on the dimensions of Roman bricks used in the Landward Wall (43 x 29.5 x 4 cm), approximately 977 bricks would have fit in each hypothetical cart; however, assuming an average weight of 10 kg per brick,[50] this would have been well beyond the carrying capacity of a standard four-wheeled cart. Consequently, only *c*. 100 bricks could have been carried per cartload, leaving roughly three quarters of the cart empty. Alternatively, if we assume that the bricks were moved on a platform with sides of ideal dimensions (*c*. 90 x 130 cm),[51] this would mean that 96 bricks (at 960 kg) could have been moved per trip. Both methods suggest a maximum of 100 bricks per load. We have based the speed of travel on estimates proposed by Roger Kendal in his examination of the transportation of materials for Hadrian's Wall: 3.2 km/h for a post-wagon (a large four-wheeled vehicle drawn by 6/8 oxen) and 4.8 km/h for a post-carriage (a large four-wheeled vehicle drawn by 8/10 mules or horses).[52] We have opted for the lower speed due to our assumed 1,000 kg cartload.[53]

In addition to the time required to move the carts, Kendal included further time for loading and unloading at 0.15 hours per 0.1 tonne;[54] however, this takes no reference to the type of material being loaded and unloaded, and seems too quick. Therefore, rates have been used from Pegoretti,[55] calculated at: 0.25 hrs/per 1,000kg for cut stone, 0.5 hrs/per 1,000kg of rubble stone, 2.5 hrs/per 1,000 bricks, 1 hr/per $m^3$of pebbles and 0.8 hrs/per m^3 of lime.

[46] Elliott 2017, 115–16. Marsden (1994, 89–89) has estimated, depending on the amount of daylight, that the vessel could travel between 85 and 140 km per day while sailing at sea and *c*. 15–22 km per day on inland waterways, which works out to speeds of 13 km/h at sea and 1.8 km/h on inland waterways. For consistency in our calculations, we have used higher speeds for inland water travel based on Elliott's (2016, 298–305) lower rate for river Thames and river Medway, at 2 knots (3.7 km/h). In comparison, Pegoretti (1869 I, 32–33) provided speeds for boat transport at 4.8 km/h when loaded and 6 km/h when unloaded.
[47] Pegoretti 1869 I, 13.
[48] The relief from the Musée de Langres shows a cart full of wine barrels being pulled by a pair of mules; Booth *et al.* 2007, 314. The dimensions have been reconstructed as *c*. 2.5 m in length, 2 m in width and 1 m in depth.
[49] Raepsaet 2009, 598–600, cf. *Codex Theodosianus* 8, 5. Pegoretti (1869 I, 19–24) stated that a two-wheeled cart could transport *c*. 1,500 kg; however, we have opted for the lower carrying capacity.
[50] Each brick would have weighed between 9.2 and 10.7 kg based on Bukowiecki and Wulf-Rheidt (2015, 46), who stated brick weights at 1,800–2,100 kg/m^3.
[51] As proposed by Bukowiecki and Wulf-Rheidt (2015, 46) for bricks; in the case of standard *sesqipedale* (44.4 x 44.4 x 3.8 cm = 7.5 cm^3), assuming a 1,000 kg limit, a total of 74 *sesquipedali* per cartload or with an ideal platform with sides based on the bricks *c*. 90 x 120 cm, a total of 60 *sesquipedali* at 810 kg.
[52] Kendal 1996, 141–143.
[53] Pegoretti (1869 I, 19–24 and 36–37) gave speeds for a two-wheeled cart travelling on flat ground of 3.6 km/h when loaded and of 5.5 km/h when unloaded, which supports the use of the lower speed given the weight being transported.
[54] Kendal 1996, 143.
[55] Pegoretti 1869 I, 26–27.

LABOUR CONSTANTS

Most studies dealing with labour calculations follow the method and labour constants proposed by DeLaine for the buildings of Rome and Ostia. DeLaine's rates are based on labour constants drawn from nineteenth-century handbooks for building surveyors, especially Giovanni Pegoretti's *Manuale pratico per l'estimazione dei lavori architettonici, stradali, idraulici e di fortificazione, per l'uso degli ingegneri ed architetti*.[56] In a Romano-British context, however, the British handbooks of John T. Hurst from 1865 and John T. Rea from 1902 have been largely adopted as the basis for labour constants.[57] Pearson, however, also augmented these figures with labour constants from Pegoretti and DeLaine.[58]

The use of different handbooks of course is problematic when one wants to compare the overall labour figures generated in other studies. For example, Shirley, Pearson and Hill all adopt different rates for laying facing blocks. Pearson used Pegoretti's figure for laying roughly cut blocks,[59] while Shirley used rates for building the perimeter wall at Inchtuthil based on Rea's constants for random rubble and for rubble stone in squared courses.[60] Hill, a trained stonemason, used a combination of rates from Rea and assumptions based on his own experience to generate labour constants for Hadrian's Wall.[61] Moreover, these authors do not make use of the labour constants given by Hurst's 1865 handbook for laying rubble stone in courses, although it should be noted that Hurst's figures are remarkably close to those of Rea. In addition to these handbooks, historical figures provide information about the labour required for certain construction activities. At Langeais castle, for example, Bernard Bachrach found that *c*. 450 "petit ashlar" blocks could be laid per 10-hour day (*c*. 0.2 p-day/m$^{2)}$.[62] For a breakdown of these rates, see Table 5.

In order to see how these rates compare, the various formulae were applied to one face of a hypothetical wall 1 x 1 x 0.2 m (Table 6). Pegoretti provided two labour figures for laying walls with stone blocks – one for cut stone and one for roughly cut stone. He also provided the same information specifically for fortification walls. The main difference between the figures is the total number of workers needed. Pegoretti's labour figures for fortifications require two additional workers (one skilled and one unskilled). As can be seen in Table 6, the rates vary from 1.6 to 2.7 (total) person-days. The laying of cut blocks for both general stone walls and fortification walls clearly required more (especially skilled) labour than the laying of rougher blocks in general stone walls. The higher person-days indicated by Pegoretti (25 to 100 per cent greater than those from the British handbooks) are due to the fact that his rates are for a higher finish of stone blocks used, and they account for the work of two builders, one or two mason(s), and one or two labourer(s), while the British handbooks only allow for one builder and one labourer. With regard to Pegoretti's figures for cut stone walls and fortification walls with both rough and cut stone, there is very little difference in terms of total person-days needed per metre cubed of wall.

[56] DeLaine 1997, 2001, Pegoretti 1863, 1864, and 1869.
[57] Shirley 2000, 96ff., Pearson 2003 and Hill 2004.
[58] Pearson 2003.
[59] Pearson 2003, 153, Appendix III. The figure is per metre cubed and is adjusted depending on the height and the thickness of the wall. The formula is for two builders, a mason and a labourer; see Pegoretti (1869 I, 139).
[60] Shirley 2000, 100. For the rate, see Rea 1902, 92–93.
[61] Hill 2004, 320–324. For example, Hill (2004, 320) rejected the figures from Rea's handbook for laying blocks, because the rate is given per cubic yard with no dimensions given for the blocks, and this makes it difficult to convert the rate to a figure per square meter, which Hill suggested would be more appropriate for laying facing stones.
[62] Bachrach (1984, 55, n. 5) drew his figures from the assumption that modern masons or bricklayers can lay forty-five units of the size ashlar block used at Langeais castle in one hour.

Overall, as can be seen in Table 6, the amount of skilled labour needed is considerably higher when using Pegoretti's rates than those of the British handbooks; however, the amount of unskilled labour specified in all of the handbooks is of the same order of magnitude. Moreover, Pegoretti's is the only manual to take into account the raising of raw materials for the height of the wall. It is also important to note that the British handbooks only have rates for the construction of walls with rubble or ashlar facing and not cut stone; however, the similarity between Pegoretti's rate for laying rough cut blocks for walls of lime mortar and the British rates for laying rubble masonry suggest that Pegoretti's rates are appropriate for use in this context.

On the other hand, the rates estimated by Hill and Bachrach are both substantially faster than those of the nineteenth-century manuals for laying facing blocks. Since Hill's rates are based on his own personal experience and directly related to the parameters of Hadrian's Wall, it is difficult to apply these to Londinium's Landward Wall. Moreover, it is difficult to check these figures against independent sources other than the nineteenth-century handbooks, which suggest that these faster rates are too quick. Both Hill and Bachrach's rates, for instance, are roughly 90 per cent faster than those of Pegoretti. Further rates for different tasks from different sources can be found in Tables 7–11. As with the rates of laying facing blocks, Pegoretti's rates are consistently higher than those given in the British handbooks and often higher still than those estimated by Hill and Bachrach.

It is difficult to know how best to overcome these differences. Ultimately, this exercise shows the caution needed when comparing labour figures from different studies. In theory, differences in labour figures should illustrate the different requirements for production, transport and construction between projects; however, the use of significantly different rates for labour constants makes this more complicated and can suggest distinctions based on material or construction that may not actually exist. To date this has not been much of an issue, because most studies that make use of labour figures concern central Italy and use Pegoretti as the standard reference for labour constants. As such studies progress, however, this is something that needs to be addressed.

In the current paper, we have opted for Pegoretti as the main source for labour requirements. This is because of the similarities noted above, as well as the fact that Pegoretti's manual is the only one with detailed information for all the stoneworking and construction tasks necessary for the Landward Wall. In addition, his handbook provides the widest variety of labour constants for production, transport and construction, and offers the additional benefit of an internally consistent source.[63] Using Pegoretti also has the advantage of providing overall production and labour figures that are much more readily comparable to figures generated for construction projects in central Italy, enabling us more accurately to compare a building project undertaken in a provincial capital with that of the capital of the Empire. Moreover, the labour requirements for the principal comparative material for Roman Britain – the Saxon Shore Forts – were also calculated from labour constants provided by Pegoretti, both directly from his handbook and through rates based on Pegoretti from DeLaine.[64] In a few cases where necessary, Pegoretti's handbook has been supplemented by labour constants given in Hurst, which is the most detailed handbook for English conditions.

[63] On this point, see DeLaine 1997, 104–109.
[64] DeLaine 1997; Pearson 2003.

TABLES FOR LABOUR CONSTANTS

The following tables provide a comparison of the rates for various production and construction tasks from historical sources (i.e. architectural handbooks) and those proposed in modern sources based on 'best estimates' through experience in the relevant field, such as Hill,[65] a practising stonemason. The comparison shows that the rates are often within $\pm$ 20 per cent of each other.

TABLE 5: LABOUR RATES FOR LAYING ROUGHLY-SQUARED FACING BLOCKS

Source	**Task**	**Unskilled**	**Skilled**
Pegoretti 1864, 136–138	Lay square or cut stone blocks (*pietre da taglio*) in lime mortar[66]	1 labourer	0.1 x (5 + (0.15 x (h–1)) + (0.2/g)) x 3 skilled p-hours/m^3
Pegoretti 1864, 138–139	Lay roughly-cut stone blocks (*pietre greggie sgrossate*) in lime mortar[67]	1 labourer	0.1 x (2.75 + (0.0825 x (h–1)) + (0.2/g)) x 3 skilled p-hours/m^3
Pegoretti 1864, 98–100	Fortification walls of square or cut stone blocks (*pietre da taglio*)[68]	2 labourers	0.1 x (a/2 + (0.015a x (h–1)) + (b/2w)) x 4 skilled p-hours/m^3
Pegoretti 1864, 100–102	Fortification walls of rough stone (*pietre lavorate a rustico*)[69]	2 labourers	0.1 x (a/2 + (0.15a x (h–1)) + (b/2w)) x 4 skilled p-hours/m^3

[65] Hill 2004.
[66] Pegoretti gave the following formula: (t/2) + 0.015 t x (h–1) + (0.2/g) x 3 skilled (+ 1 assistant) per m^3, where t = 10 hours per m^3 of wall, h = the height of the wall and g = the thickness of the wall.
[67] Pegoretti gave the following formula: (t/2) + 0.015 t x (h–1) + (0.2/g) x 3 skilled (+ 1 assistant) per m^3, where t = 5.5 hours per m^3 of wall, h = the height of the wall and g = the thickness of the wall.
[68] Pegoretti's figures are for two builders, two stonecutters and two labourers. h = the height of the wall and w = the thickness of the wall. The variables a and b differ based on the type of construction, the weight of the stone and whether the wall has 1 or 2 faces with a ranging from 8–15 and b ranging from 0.1–0.3 hours per m^3. For a wall with stones less than 80 kg, a = 8 hours. For a wall with one face, b = 0.1 hours.
[69] Pegoretti's figures are for two builders, two stonecutters and two labourers. h = the height of the wall and w = the thickness of the wall. The variables a and b differ based on the type of construction, the weight of the stone and whether the wall has 1 or 2 faces with a ranging from 4–8 and b ranging from 0.1–0.3 hours per m^3. For a wall with stones less than 80 kg, a = 4 hours. For a wall with one face, b = 0.1 hours.

Rea 1902, 93	Rubble walling in squared courses in lime mortar[70]	0.65 p-days/m^3 x 1	0.65 p-days/m^3 x 1
Hurst 1865, 217	Lay rubble masonry in courses with mortar[71]	0.63 p-days/m^3 x 1	0.63 p-days/m^3 x 1
Hill 2004, 422	Lay squared rubble in mortar[72]		0.05 p-days/m^2 x 3 skilled
Bachrach 1984, 51	Lay 'petit ashlar' walling[73]		0.2 p-days/m^2

TABLE 6: COMPARISON OF LABOUR RATES FOR
LAYING ROUGHLY-SQUARED FACING IN MORTAR

Source	**Task**	**Skilled p-days**	**Unskilled p-days**	**Total p-days**
G. Pegoretti 1864	Lay cut stone blocks for walls of lime mortar	1.9	0.6	2.5
G. Pegoretti 1864	Lay rough cut blocks for walls of lime mortar	1.2	0.4	1.6
G. Pegoretti 1864	Lay cut stone blocks for fortifications	1.8	0.9	2.7
G. Pegoretti 1864	Lay rough stone blocks for fortification	1.5	0.8	2.3
J. T. Rea 1902	Lay rubble walling in square courses	0.65	0.65	1.3
J. T. Hurst 1865	Lay rubble masonry with horizontal beds	0.63	0.63	1.3
P. Hill 2004	Lay rough-squared blocks	0.2	–	0.2
B. S. Bachrach 1984	Lay 'petit ashlar' facing	0.2	–	0.2

[70] Rea's rate for rubble walling in lime mortar is as follows: 3 person-hours per cubic yard for one waller and one labourer. For walling in squared courses in lime mortar, 5 person-hours per cubic yard for one waller and one labourer with the addition of 0.5 person-hours if the joints are pointed. If we convert these figures to cubic metres, the rates are as follows: 3.9 person-hours and 6.5 person-hours per cubic metre, for one waller and one labourer respectively, with pointing at 0.65 person-hours extra per cubic metre.
[71] Hurst (1865, 217) gave a rate of 0.48 person-days per cubic yard for one labourer and one mason.
[72] Hill's figures are as follows: three workers to lay facing stones at 32 minutes per square metre. The typical size of stone (square rubble) at Hadrian's Wall given by Hill (2004, 321) is 260 x 380 x 180 mm, which he used for calculating the construction rates. For mortar, he allowed 6 mm for bed joints and 12 mm for vertical joints, which provided an average figure of *c.* 20 per m^2 of wall (Hill 2004, 321). Hill did not distinguish between skilled and unskilled labour. We have assumed all three are skilled labourers.
[73] Bachrach (1984, 55, n. 5) gave his figures as 45 units (i.e. blocks 10 x 10 x 15 cm) per hour, for a total of 450 per 10-hour day, with 320 person-days needed for the total of 144,000 "petit ashlar" blocks (1,600 m2)

TABLE 7: LABOUR RATES FOR QUARRYING

Source	Task	Unskilled	Skilled
Pegoretti 1863, 159	Quarrying soft limestone	2 x skilled	1.75 p-days/m^3
Rea 1902, 88	Quarrying limestone or other stratified rock		1 p-day/5–8 tonnes
Pearson 2003, 153	Quarrying harder lithologies: e.g. Kentish Ragstone[74]	0.58 p-days/m^3	
Pearson 2003, 153	Quarrying soft lithologies: e.g. Sandstones	0.26 p-days/m^3	
Hill 2004, 424	Quarrying stone blocks[75]		0.7 p-days/m^3 x 2 skilled

TABLE 8: LABOUR RATES FOR DRESSING STONE FACING BLOCKS

Source	Task	Unskilled	Skilled
Pegoretti 1863, 430	Rough dressing for regular ashlar masonry, soft limestone		2.7 p-hours/m^2
Morisot 1820–4	Rough dressing for regular ashlar masonry, soft limestone		2.1–2.7 p-hours/m^2
Claudel & Laroque 1863	Rough dressing for regular ashlar masonry, soft limestone		2 p-hours/m^2
Hill 2004, 424	Dressing facing stones (@ 5 minutes per stone)	1 worker per 2 dressers	12 facing stones per hour x 2 skilled
Salzman 1967, 103–104; 1923, 90–91	For a mason to cut and face ashlar blocks[76]		1.8 p-days/m^2

[74] This figure is based on Hurst (1865). The present authors could only find one quarry figure in Hurst (1865, 202), which provided a rate of between five to eight tonnes of stone per day for one quarry worker. It is assumed that Pearson calculated his person-days per cubic metre based on this rate taking into account the weight of the stone.
[75] Hill suggested a rate of 7 stones (0.012 m^3 each) per 35 minutes for 2 workers.
[76] The historical figures for the later Middle Ages in England suggest a mason could cut and face c. 864 inches squared of ashlar per day (the equivalent of 1.8 p-days/m^2). In Medieval England, the size of ashlar was standardized. For the rates, see Salzman (1923, 90–91; 1967, 103–104).

TABLE 9: LABOUR RATES FOR QUARRYING RUBBLE

Source	Task	Unskilled	Skilled
Rea 1902, 88	Quarrying limestone or other stratified rock		5–8 tonnes per day x 1 skilled
Hurst 1865, 202	Quarrying stone		5–8 tonnes per day x 1 skilled
Pegoretti 1863, 183	Quarrying boulders between 0.33–0.67 kg for breaking into rubble	0.2 p-days/m^3	
Hill 2004, 424	Quarrying stone for rubble		8 tonnes per day

TABLE 10: LABOUR RATES FOR BREAKING-UP STONE INTO RUBBLE

Source	Task	Unskilled	Skilled
Pegoretti 1863, 183	Breaking stone into rubble	1 p-day/m^3 of rubble	
Hurst 1865	Breaking stones to a size that will pass through a ring 1½ inches in diameter		7 hours per cubic yard
Hill 2004, 424	Breaking sandstone with a hammer[77]		16 tonnes per day

[77] Hill based his rate on War Office (1911) records that give a figure of 2 tonnes an hour for breaking moderately hard rock.

TABLE 11: LABOUR RATES FOR LAYING RUBBLE AND MORTAR FOR WALL CORE

Source	Task	Unskilled	Skilled
Pegoretti 1864, 145–146	Lay core, where *h* = the height of the wall	1.5 x skilled	4.01 + 0.12 (h–1) p-days/m^3
Hill 2004, 422–423	Lay core and clay bonding		72 minutes per m^2 x 3 workers and 38 minutes per m^2 x 4 workers
Bachrach 1984, 51	Fill the core with stone and mortar		2.5 m^3 per day

LABOUR CONSTANTS FOR PRODUCTION

The following assumptions have been made regarding the production of materials for Londinium's Landward Wall. In the case of Kentish ragstone, it is assumed that the volume for transport increases by 50 per cent when broken into rubble,[78] which must be taken into account when calculating requirements for loading, unloading and transport. As DeLaine has suggested,[79] a distance of 25 m from the working face for further processing has been assumed in all cases, except lime, which has been estimated at 100 m, and the labour for loading and unloading has been added at this stage. It also has been assumed that the finished product was loaded into carts, where they were processed without further carrying by labourers. Moreover, time for supervision and administration has been added at a rate of 10 per cent of the total productive labour, and it is assumed that these activities were undertaken by skilled labourers.[80] All figures for transport (loading, unloading, carrying, etc.) have been taken from Pegoretti and supplemented by Hurst when necessary.[81] The maximum load one worker can carry is assumed to be *c*. 50 kg.[82] Further specific details relating to the rates can be found in the footnotes below. The tasks and labour estimates for the materials/elements used in the Landward Wall can be found in Tables 12–15.

TABLES FOR LABOUR PRODUCTION CONSTANTS

TABLE 12: ESTIMATED LABOUR CONSTANTS FOR BRICK PRODUCTION (ASSUMING A LARGE KILN OF 100 M^3 OVERALL VOLUME)[83]

Task[84]	Unskilled p-days	Skilled p-days
Quarry 2,148 m^3 of clay	322	–
Load and carry	1,357	–
Prepare clay and form 421,176 bricks[85]	1,685	1,685
Load kiln[86]	210	105
Fire kiln using 538 t wood	115	115
Unload	138	–
Total	3,827	1,905
Supervision and administration	–	573
Total/1000 + 2.44 tonnes fuel	9.1	5.4

[78] DeLaine 1997, 110.
[79] DeLaine 1997, 110.
[80] DeLaine 1997, 111.
[81] Pegoretti 1863, 26–27, 155–158 and Hurst 1865, respectively.
[82] DeLaine 1997, 107.
[83] McWhirr and Viner (1978, 360) summarised the Roman brick/tile manufacturing process, which typically began in autumn with the excavation of the clay. After this, the clay was allowed to weather over the winter. This was followed by the shaping of the bricks or tiles using a wooden frame or mould, sometimes the bricks/tiles were stamped. The bricks or tiles would be left to harden and were then fired in a kiln. At this point, the bricks/tiles could be stored or directly transported to the construction site or customer.
[84] Labour constants are based on those used by DeLaine (1997, 114–118), which derive from Pegoretti (1863, 286–299) who provided values for making bricks of different sizes, some of which are close equivalents to imperial Roman types. The total number of bricks per kiln load is 18,312 bricks.
[85] We have assumed a daily rate of 250 bricks based on Pegoretti (1863, 299), the closet equivalent to our Roman brick size.
[86] Based on Pegoretti (1863, 298), who provided figures for loading bricks similar in size to those used in the Landward Wall into a kiln at 0.125 p-days for 2 skilled and 4 unskilled workers for 1,000 bricks.

TABLE 13: ESTIMATED LABOUR CONSTANTS FOR QUICK LIME PRODUCTION (ASSUMING A LARGE KILN OF 100 M^3 OVERALL VOLUME)[87]

Task[88]	**Unskilled p-days**	**Skilled p-days**
Quarry chalk 66 m^3 and break	66	66
Load into baskets[89] and carry 100 m	25	–
Load kiln	14	7
Fire kiln using 165 t wood	14	14
Unload kiln and load into carts	16	–
Total	135	87
Supervision and administration	–	22
Total/m^3 + 2.75 tonnes fuel	2.25	1.82

TABLE 14: ESTIMATED LABOUR CONSTANTS FOR ROUGHLY-SQUARED FACING STONE AND RUBBLE PRODUCTION

Task	**Facing stones**[90] **(5,325 m^3 / 739, 562 blocks)**		**Rubble**[91] **(16,048 m^3)**	
	Unskilled p-days	**Skilled p-days**	**Unskilled p-days**	**Skilled p-days**
Quarry Kentish ragstone	18,638	9,319	3,210	–
Load and carry 25 m	632	–	3,172	–
Process	–	116,112	16,048	–
Load into carts	351	–	9,629	
Total	19,621	125,431	32,059	–
Supervision and administration	–	14,505	–	326
Total/m^3	3.7	26.3	2.0	0.02
Total/1000	26.5	189	–	–

[87] After DeLaine 1997, 113, Table 7. DeLaine (1997, 189) assumed a unit of 14 workers, producing 60 m^3 of quicklime per cycle and 14 cycles per year.
[88] Again, the labour constants are based on those used by DeLaine (1997, 112–114) for lime production, which derive from recorded firing from later periods and experimental firings at Iversheim; Sölter 1970, 40.
[89] The volume of a basket is assumed to be a 2-*modius* basket with a capacity of *c*. 1 cubic Roman foot (0.026 m^3); DeLaine 1997, 107.
[90] For stoneworking, see the tables in Pegoretti (1863, 429–437). The rate of quarrying is calculated as for 'pietra calcarea tenera' (soft limestone) at a rate of 1.75 p-days/m3 for one skilled and two unskilled labourers (Pegoretti 1863, 159). Our processing figure includes labour for rough squaring of the blocks at a rate of 4.5 hrs/m^2 (Pegoretti 1863, 281), rough dressing for hidden work at 1.75 hrs/m^2 and rough dressing for regular ashlar masonry at a rate of 2.67 hrs/m^2. These equate to rates of 0.45 p-days/m^2, 0.18 p-day/m^2 and 0.27 p-days/m^2 for one skilled labourer, respectively. We have assumed that the whole block is roughly squared but only the visible face of the block is roughly dressed for regular ashlar masonry with the remaining sides being only roughly dressed for hidden work.
[91] Pegoretti (1863, 183) gave a rate for quarrying boulders for breaking into rubble at 0.2 p-days/m^3 for 1 labourer. For breaking into rubble, Pegoretti (1863, 183) gave a rate of 1 p-day/m^3 of rubble for 1 labourer. Pegoretti also gave rates for loading and unloading, 0.06 p-days/m^3 and 0.075 p-days/m^3 for 1 labourer for this kind of material.

TABLE 15: ESTIMATED LABOUR CONSTANTS FOR PLINTH AND COPING STONE PRODUCTION

Task	**Plinth stones[92] (119 m³ / 5,948 blocks)**		**Coping stones[93] (612 m³ / 1,457 blocks)**	
	Unskilled p-days	**Skilled p-days**	**Unskilled p-days**	**Skilled p-days**
Quarry	596	298	2,142	1071
Load and carry	15	–	72	–
Process	–	2,428	–	5,653
Load into carts	8	–	40	–
Total	619	2,726	2,254	6,724
Supervision and administration	–	334	–	898
Total/m³	5.2	25.7	3.7	12.5
Total/1000	104	514	1,547	5,231

LABOUR FIGURES FOR THE LANDWARD WALL

The following section provides a detailed examination of the total labour needed to construct the various elements of the Landward Wall – the v-shaped ditch and earthen rampart, the foundations, the chamfered plinth, the wall (including the brick bonding-course and crenellation) and the installation of the coping stones. Each of these aspects is dealt with in turn below. As with the calculation of labour for production, the quantity of labour for construction is based on constants from nineteenth-century handbooks (see above). The constants have been adjusted to account for ancient conditions and have been selected in light of the construction techniques used for the Landward Wall. The labour constants were then applied to the quantities of materials calculated in Table 4 above. The details of the rates and totals can be found in Table 16 below.

92 We have assumed the following stages based on Pegoretti's tables for 'pietra arenaria' (1863, 159, 446–450): quarrying (2.5 p-days/m³ x 1 skilled and 2 unskilled labourers), rough squaring (0.67 p-days/m² x 1 skilled labourer), cutting back, i.e. along one plane (3.1 p-days/m³ of material removed x 1 skilled labourer), rough dressing for hidden work (0.17 p-days/m² x 1 skilled labourer) for the non-visible faces of the block and rough dressing for regular ashlar masonry (0.25 p-days/m² x 1 skilled labourer) for the visible faces of the block plus dressing with bush hammer or tooth chisel (0.33 p-days/m² x 1 skilled labourer).

93 We have assumed the following stages: quarrying (at 1.75 p-days/m³ for one skilled and two unskilled labourers), rough squaring (at 4.5 p-hrs/m²), shaping of a profile (5.69 p-days/m³ of material removed x 1 skilled labourer) and rough dressing of a curved surface (calculated at 0.175 p-days (1+0.25/x) per m², in which *x* is the diameter of the curve). Again, dressing for hidden work (0.18 p-day/m²) has been assumed for non-visible faces on the blocks, but for the visible surfaces we added dressing of a curved surface for the top of the blocks (0.44 p-days/m²) and dressing of a flat surface for the sides of the blocks (0.33 p-days/m²).

V-SHAPED DITCH AND INTERNAL BANK OF EARTH

Contemporary with the construction of the Landward Wall was a v-shaped ditch[94] and perhaps the setting of a bank of earth against the internal faces of the wall.[95] The bank appears to have been formed in multiple phases. Whipp noted that the bank may have been constructed in two phases of tipping, with the bank being built up as the masons gradually increased the height of the wall.[96] Excavation at 8–14 Cooper's Row revealed that the bank was formed from three separate layers of soil dumped at different times.[97] It has been assumed that the excavated earth from the v-shaped ditch was only removed a short distance of 25 m for the construction of the earthen bank after the construction of the wall masonry.[98] Assuming that the v-shaped ditch was only built along the eastern side of the defences,[99] we estimate that digging the v-shaped ditch would have required 877 person-days (including supervision) to complete. For the construction of the internal bank of earth, we have assumed that the earth needed came from the digging of the foundations and v-shaped ditch. Therefore, this material only had to be transported to the wall and used for the earthen bank. The rate for the latter was drawn from construction experiments at Teotihuacan (Mexico) that were designed to assess the duration and timing of monumental construction.[100] In total, the internal earthen bank would have required 4,676 person-days (including supervision) to create. It is not clear if the internal bank was turfed. If it was, this would have added to the construction requirements;[101] however, without evidence for such construction, we have excluded turf from our calculations.

We can compare the figure for Londinium with other earthen ramparts created for defences. For example, the ramparts at the fortress at Inchtuthil have been estimated at 475,140 person-hours, which included cutting and transporting the turfs as well as excavating and transporting the soil, and shaping and turfing the front of the slope.[102] An estimate of the labour required for the earthen defences at Silchester, constructed in the late second century, was 300–

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[94] Merrifield 1965, 105, fig. 12 and Maloney 1979, 295 and 1980, 68.

[95] Marsden 1970, 3–4 and Maloney 1979, 295. Whipp (1980, 50) noted that the inner rampart must have been built after the Landward Wall but not long after, and so was part of the original construction phase. Parnell (1982, 94) noted that the mortar pointing on the inner face of the wall was so well preserved that it must have been protected immediately after application by the construction of the bank. Maloney (1983, 101) has argued along similar lines, stating that 'doubtless the material used in its formation was the upcast from the foundation trench and perhaps the ditch; the dumps of predominantly 'clean' natural deposits successively tipped against the wall may indicate the bank was formed in stages perhaps corresponding to those in the construction of the wall.' More recent excavation at 8–14 Cooper's Row suggests that the earthern rampart could have been a later addition, though the lack of precise dating evidence means that it is not possible to be certain (Hunt 2010, 55, 58).

[96] Whipp 1980, 50.

[97] Hunt 2010, 55.

[98] Marsden 1970, 3–4, Maloney 1979, 295 and 1983, 101. Whipp (1980, 50) noted that the bank consisted of yellow-brown sandy clay and most likely came from the wall construction trench and external defensive ditch, although fragments of ragstone, brick and mortar were also present. The cross-section excavation showed tip lines sloping down from east to west. Parnell (1982, 94) also concluded that the earth from the bank must have been derived from the excavation of the wall and its ditch. Vegetius also mentions that ramparts were built using 'earth which has been dug out of the ditches' (4.3).

[99] Maloney 1979, 295 and 1980, 68. Merrifield (1965, 105 fig. 12) noted that the v-shaped ditch has been identified at various points on the course of the Landward Wall; however, it has not yet been positively identified on the western side of the circuit. We have therefore only included figures for the eastern side of the defences.

[100] Murakam 2015. These seem better than the rates used by Shirley 2000 and Hobley 1971.

[101] For new work on energetics related to earth and turf construction, see Snyder *et al.* (forthcoming). While the type of turfing used in connection with the Landward Wall is not fully explored in this paper, it would mostly likely not have added a great deal of labour, as long as the turf was sourced close to the course of the wall.

[102] Shirely 2000, 111.

350,000 person-hours (30,000–35,000 person-days).[103] Here, a total of 71,370 m^3 of clay and gravel had to be excavated from two ditches.[104] This figure is much greater than the 34,640 m^3 excavated for the inner and outer ditches at Caewent, which measured 1,829 m and had similar cross-sectional dimensions to Silchester.[105] Caerwent is estimated at roughly half the labour requirements for Silchester, 150–175,000 person-hours (15,000–17,500 person-days).[106] The larger earthen ramparts at Verulamium, roughly 1.6 times the volume of Silchester, are estimated at 450–525,000 person-hours (45,000–52,500 person-days).[107] In the case of Silchester, a work-force of *c*. 300 would have been able to complete the entire work in 100–120 days of 10 working-hours.[108]

FOUNDATIONS

The foundation trenches of the Landward Wall are variable but are generally 2.6 m wide with a depth between 0.88 and 1.17 m.[109] In addition, subsoil timber piles were used when there were issues of stability.[110] Although we have not calculated the labour or material needed for this task due to the uncertainty of the length of wall that required the use of timber piles in the foundations,[111] these aspects should not be underestimated and may have added a reasonable number of person-days to the project.[112] The excavation of the foundation trench would have required 2,185 person-days with a further 2,811 person-days to remove the debris 25 m, for a total of 4,996 person-days (excluding supervision). Again, we have assumed that the excavated earth would have been used to construct the internal earthen bank. For the remaining elements of the foundations – digging and puddling the clay, mixing the clay with pebbles into the foundation, slaking the lime, laying the rubble foundations, mixing the mortar and fetching the materials – a further 5,974 person-days would have been needed. In total, including supervision, the construction of the foundations therefore would have required 12,144 person-days.

[103] Fulford and Startin 1984, 241 and Startin 1984.
[104] Fulford and Startin 1984, 241.
[105] Nash-William 1930, fig. 11, pl. lxxxv.
[106] Fulford and Startin 1984, 241.
[107] Fulford and Startin 1984, 241.
[108] Fulford and Startin 1984, 242.
[109] Maloney 1983, 98.
[110] i.e. Merrifield 1965, 304, W18 and 1969, 118–119. Sections of the Landward Wall uncovered and removed in 1861 at Jewry Street near Aldgate were described by Loftus Brock (1880, 163) as 'of Roman construction throughout and [resting] on massive piles which had been driven for a foundation on account of the badness of the soil.' Those used in the foundations of the Riverside Wall were squared oak piles and measured on average 0.2 x 2–2.6 m. The piles were arranged in five rows; see Hill *et al.* 1980, 29–30, fig. 18 and plates 2, 4, and 7.
[111] In the case of the better-documented use of timber piles in the Riverside Wall, these timbers were only used in certain areas where the subsoil was unstable. In total, *c*. 38 m of the total 115-m length of the Riverside Wall uncovered during the 1970s excavations across Upper Thames Street used timber piles in the construction of the foundations. Supporting timber piles were used only on the eastern sections of the wall (Area I and VI), while the foundation of the western sections (Areas III, VII and VIII) of the Riverside Wall, where the subsoil consisted of solid clay, were without piles; see Hill *et al.* 1980, 57–61.
[112] Pearson (2003, Appendix III) estimated that three piles could be cut per day and 75 piles driven into the foundations per day. In the case of the Riverside Wall, Hill *et al.* (1980, 30) estimated that at least 750 timber piles were used in the 38-m stretch of the Riverside Wall documented in the 1970s excavations across Upper Thames Street. Using figures given by Pearson, this would require 250 person-days to cut the piles and a further 10 person-days to drive the piles into the foundations. We must also remember that these figures do not include transport.

WALL UP TO 4.4 M

The construction of the Landward Wall (up to a height of 4.4 m) above the foundation and below the crenellation and coping stones accounts for the majority of the labour and materials needed for the whole construction project. This would have included the laying of the chamfered plinth blocks (176 person-days), the laying of the facing blocks on both sides of the wall (5,650 person-days), the laying of the four brick bonding courses (537 person-days) and the building of the rubble core (3,255 person-days), for a total of 9,618 person-days. This estimate increases to 22,598 person-days if we take into account the labour necessary for other tasks, such as mixing the mortar, fetching the materials, raising the materials, erecting the scaffolding and supervision.

WALL ABOVE 4.4 M: CRENELLATION AND COPING STONES

The estimated labour figure for the remaining elements of the Landward Wall's construction – the crenellation and the coping stones – is 6,427 person-days, including supervision. The majority of the labour costs for this section of the wall was evenly distributed between the labour required for laying the facing blocks at 2,295 person-days and the lifting and positioning of the coping stones at 2,460 person-days. It should be noted, therefore, that the installation of the coping stones also required a significant percentage of the total labour for this portion of the wall's construction – roughly 42% (excluding supervision).

TABLE 16: ESTIMATED LABOUR FOR BUILDING THE LANDWARD WALL IN PERSON-DAYS (P-DAYS) OF LABOUR

Landward Wall		**V-shaped ditch**	**Internal earth bank**	**Foundations**	**Facing**	**Bonding-course**	**Core**	**Crenellation**	**Total**
Total volume (m^3)		2,459	12,750	15,606	3837	2372	21,703	2681	48,694
Number of Bricks		–	–	–		421,176	–	–	421,176
Stone blocks in plinth		–	–	–	5,948	–	–	–	5,948
Stone blocks in facing		–	–	–	478,590	–	–	260,972	739,562
Rubble pieces		–	–	361,125	–	–	1,649,375	–	2,010,500
Stone blocks in coping		–	–	–	–	–	–	1,457	1,457
Puddled clay (m^3)		–	–	1,768	–	–	–	–	1,768
Pebbles (m^3)		–	–	884	–	–	–	–	884
Quicklime (m^3)		–	–	155	36	28	707	24	950
Mortar (m^3)		–	–	1,238	287	224	5,655	190	7,594
Task	**Labour rate**	**Total p-days**	**Total p-days**	**Total p-days**	**Total p-days**	**Total p-days**	**Total p-days**	**Total p-days**	**Total p-days**
Digging foundations and throwing out, ≤ 1.6m deep[113]	0.14 d per m^3	344	–	2,185	–	–	–	–	2,529
Removing debris over 25 m[114]	0.001 d per trip + 0.145 d per m^3	453	–	2,881	–	–	–	–	3,334
Moving and tipping earth 25 m[115]	0.001 d per trip + 0.145 d per m^3	–	2,339	–	–	–	–	–	2,339
Creating the earthen bank[116]	0.15 d/m^3	–	1,912	–	–	–	–	–	1,912

[113] Pegoretti 1863, 241–245.
[114] Pegoretti 1863, 157.
[115] We have assumed the same rate as loading and moving for this process.
[116] Based on rates given in Murakami (2015, 201, 269, table 1) from construction experiments at Teotihuacan, Mexico.

Digging clay and throwing behind[117]	0.15 d per m^3	–	–	265	–	–	–	–	265
Puddling clay and spreading in layers with pebbles[118]	0.86 d per m^3 + 0.0052 d per m^2	–	–	1,553	–	–	–	–	1,553
Slaking lime, per volume of quicklime[119]	1.2 d per m^3	–	–	186	43	34	848	29	1,140
Laying rubble foundations, where d = depth of foundation[120]	0.35 d per m^3	–	–	1,011	–	–	–	–	1,011
Mixing mortar, foundations[121]	0.55 d per m^3	–	–	681	–	–	–	–	681
Fetching material	0.146 d per m^3	–	–	2,278	560	346	3,169	391	6,744
Laying chamfered plinth blocks, where t = 10 hrs per m^3 of stone, h = the height of the wall and g = the thickness of the wall[122]	0.1 x ((t/2) + (0.15t x (h–1)) + (0.2/g)) x 3 skilled (+ 1 assistant)	–	–	–	176	–	–	–	176
Laying facing blocks, where h = the height of the wall, w = the thickness of the wall, a = 4 hours, and b = 0.1 hours[123]	(0.1 x (a/2 + (0.15a x (h–1)) + (b/2w)) x 3 skilled (+ 2 assistant) per m^3 of wall	–	–	–	5,650	–	–	2,295	7,945

[117] Pegoretti 1869 I, 155.
[118] Hurst 1865, 213. To this figure we have added the time needed for spreading the pebbles within the puddled clay, estimated as twice the rate given by Hurst (1865, 220) for spreading broken stone in thicknesses of 3 inches in order to account for the larger depth that the pebbles needed to be spread within the puddled clay.
[119] Pegoretti 1864, 132.
[120] Pegoretti 1864, 132–133, for laying foundations and mixing mortar. The rate for foundations is 0.35 + 0.01 (d–1) person-days per m^3.
[121] Pegoretti 1864, 145.
[122] Pegoretti 1864, 136–137.
[123] Pegoretti 1864, 100–102

Laying core, where h = the height of the wall, w = the thickness of the wall, and a = 0.7 hours.[124]	(0.1 x (a + 0.03a x (h–1)) + 0.4/w) per m^3 x 1 skilled + 0.5 d for assistant	–	–	–	–	–	3,255	–	3,255
Laying brick for bonding courses, where t = 0.75 hour per 100 bricks, h = height of the wall, w = thickness of the wall[125]	t + 0.03t (h–1) + 0.4/w d per m^3 x 1 skilled + 0.5 d for assistant	–	–	–	–	537	–	–	537
Mixing mortar, walls	0.7 d per m^3	–	–	–	201	20	3,958	17	4,196
Preparation for lifting, 2 masons, 1 stonecutter and 1 labourer[126]	0.2 hours per tonne of stone	–	–	–	–	–	–	128	128
Raising and positioning coping stones for 2 masons, 1 stonecutter, and 1 labourer[127]	0.625 hours per tonne per metre lifted + 0.1 hours per tonne for positioning blocks	–	–	–	–	–	–	2,332	2,332

124 The rate provided by Pegoretti (1864, 145–146) was adjusted to the parameters of this wall, based on the methodology provided by DeLaine (1997, 268, Appendix 5), which gives a rate of 0.1 person-days skilled labour and 0.05 person-days unskilled labour per m^3.

125 Pegoretti 1864, 105–106. The formula is t + 0.03 x t (h–1) + b/w, with t = 0.75 hour per 100 bricks, b = 0.40 hours for a two-faced wall, h = height of the wall, and w = width of the wall. The figure includes 1 bricklayer, 2 unskilled workers and 1 supervisor.

126 Pegoretti 1864, 14–15.

127 Pegoretti 1864, 217–218, and 14–15, for different types of lifting apparatus. Pegoretti's figures are based on the size of the block being raised, with different sizes requiring different lifting apparatuses and more workers. Larger blocks require the use of more complex systems of pulleys, winches and hoists, while blocks under 80 kg can be lifted without specialist equipment. Blocks between 0.3 and 0.6 tonnes require only an A-frame and simple hoist, with one labourer operating the hoist and a stone mason, stonecutter and two labourers to assist in putting the block in place. The coping stones used in the wall each weigh *c.* 1.1 tonnes. For this size of block, Pegoretti gave a basic figure for the motive force of one labourer for every 0.625 tonnes at a rate of 0.25 hour per metre raised with additional workers needed in the case of larger blocks. The number of workers needed varied according to the height the block was raised (Pegoretti 1864, 15): from five to eight skilled workers and one to two labourers depending on the height, plus one supervisor. The size of the coping blocks required two workers operating the hoist at Pegoretti's rates. For the number of workers needed to assist in putting the blocks in place, Pegoretti (1864, 217) stated that two stone masons, one stonecutter, one labourer and one supervisor are needed. The formula is t + 0.06 (h–1), where t is equivalent to 0.50–0.60 hours, depending on the weight of the block, and h the height at which the blocks themselves are to be raised. For blocks of considerable volume and with weights of over 1,000 kg, an additional 3 labourers are required. For blocks of this weight the rates are 0.20 hours for tying up, 0.33 hours per metre of distance from the wall, 0.20 hours for raising to every meter of height and 0.10 hours for the final installation per tonne. The figure omits the cost of the lifting equipment and the person-hours needed to set up the equipment.

Raising materials, h = height of wall[128]	0.012 (h–1) d per m^3	–	–	–	55	34	312	153	554
Erecting scaffolding[129]	0.063 d per m^2 face including 2 assistants	–	–	–	1,349	–	–	498	1,847
Subtotal		**797**	**4,251**	**11,040**	**8,034**	**971**	**11,542**	**5,843**	**42,478**
Supervision	10% of total	80	425	1,104	803	97	1,154	584	4,247
Total		**877**	**4,676**	**12,144**	**8,837**	**1,068**	**12,696**	**6,427**	**46,725**

[128] Pegoretti 1864, 243.
[129] Pegoretti 1864, 6–7. We have assumed scaffolding was needed on both sides of the Landward Wall during its construction; however, it is possible that the construction of the internal earthen bank eliminated or reduced the need for scaffolding on the wall's interior side. Whipp (1980, 50) noted that the sections of the internal bank discovered during excavations immediately north of the Tower of London were constructed in two tipping phases. Cross-section of the bank showed that the tip layers were separated by a layer of *c*. 0.10 m of loose mortar, ragstone chips and pebbles, which Whipp interpreted as accidental spillage of building debris from the wall on the top of an incomplete bank. He suggested therefore that the rampart was built up in stages as the masons increased the height of the wall with each successive stage of the bank providing the masons access to the next course of the wall to be built; however, Whipp (1980, 50) noted that insufficient rampart survived to test this theory over a significant area.

LABOUR FORCE ASSUMPTIONS

In order to consider the work-force that would have been needed for various tasks, several variables, such as the length of the construction season and the physical spacing of workers engaged in various activities, need to be addressed. For example, it has been assumed that one person can only dig a surface area of 4 m^2 or larger and can be no closer than 2 m to his neighbours in any direction.[130] In the case of the v-shaped ditch, we have assumed a surface area for the middle of the ditch as an average, because the number of workers able to dig at the top of the ditch would have decreased the further the work progressed. The maximum number of diggers that could have constructed the v-shaped ditch, therefore, would have been 26 workers per 25-m length, with each person operating within a 4 m^2 section and excavating 10.2 m^3 of material. This translates into 0.9 days required to dig each 25-m section of the ditch, including the addition of a further 33.5 workers for removing the spoil. For the internal earthen bank, assuming the parameter of each person working within a 4 m^2 section, a total of 32 workers could have worked within each 25-m stretch. The process of constructing 25 m of the internal earthen bank could have been completed in 0.6 days with 32 workers and a further 39 workers to supply the earth.

Using the same parameters and assumptions outlined for the v-shaped ditch, the excavation of the foundations in 25-m lengths (*c.* 65 m^2, with a maximum depth of 1.02 m) would have employed a maximum of 16 workers at one time. The excavation of the foundations, therefore, would have required a total of 1.3 days with each person in his 4 m^2 area excavating 4.1 m^3 of material. A further 22 workers would have been needed to remove the spoil and keep up with the work-force digging the foundations. At this rate, the whole foundations could have been excavated and the spoil removed in half a season.

The calculation of a workforce for the construction of the foundations is less straightforward.[131] For the pebble and puddled clay foundations, where the depth was greater than 1 m, the filling and spreading must have been done by a person standing in the trench, with a further 1 worker puddling the clay (i.e. mixing clay with water). If the widest area that each worker could fill was 5.2 m^2 (2.6 m (the width of the foundation trench) by 2 m in length), 12.5 workers could have fit in a 25-m section of foundation trench. This would allow a combined work-force of 25 workers per 25-m length of foundation requiring 0.6 days. If we assume the same parameters for laying the mortared rubble foundations, with 12.5 workers in the trench and 8.5 workers mixing the mortar, it would take 0.8 days per 25-m length of foundation for the 21-strong work-force. To this figure, we need to add 16 workers per 25-m length for fetching the foundation materials. The combined labour requirements for the construction of the foundations, therefore, would have been a minimum of 2.7 days per 25-m length, with a constant work-force of 38 workers for digging the foundations and 62 workers for laying the foundations, with additional labour for supervision in both cases. This translates into half of one season for 38 workers to dig the foundations and just over half a season for 62 workers to lay the entire foundations.

If we now turn to the construction of the wall, we can assume that for each 25-m section, based on a spacing of one person every 1.85 m (see 'Assumptions' above), a maximum of 14 workers would have been engaged on each face in tasks, such as laying facing blocks or bricks, for a maximum work-force of 28 workers per 25-m section of the wall at one time. If we assume the wall was constructed to its full height in lengths of 25 m,[132] a total of 2.2 days for a work-

[130] Based on DeLaine 1997, 183.

[131] DeLaine 1997, 184, for the methodology.

[132] Maloney (1983, 98) noted that the Landward Wall was most likely built in 25-m stretches, based on the observation of 'numerous breaks in the levels of the bonding courses' and variations in construction (see *RCHM* 1928, 72), which he attributes to the presence of different gangs of builders.

force of 28 workers would have been needed for the facing (including the brick bonding-course) per section with an additional 1 person for mixing the mortar and 4.5 workers for fetching and raising materials. For the chamfered plinth and the coping stones used in the wall's crenellation, a total of 14 workers could have been engaged for 1.8 days on a 25-m stretch due to the fact that these elements were only present on one face of the wall. For the construction of a 25-m stretch of the rubble core, a constant work-force of 48 workers could have been employed for 2.7 days with 12 workers laying, 14 workers mixing the mortar and 12 workers fetching the materials. Additional labour for supervision would have been required in all cases.

This translates into a construction time for the whole wall of 59 workers for 27 days to dig the v-shaped ditch, 38 workers for 133 days to dig the foundations, 62 workers for 143 days to lay the foundations, 96 workers for 683 days to build the wall to its full height above the foundations and finally 71 workers for 61 days to build the internal earthen bank, for a total of 1,047 days (just under four 270-day building seasons) with a total workforce of 326 workers. This assumes that for each 25-m stretch of wall that was built no one worked on more than one task within a 25-m stretch at the same time but proceeded to the next 25m-stretch.

Alternatively, if we take a higher figure of 10 lengths (250 m of wall) under construction at the same time with a larger workforce, the wall could have been constructed at a much faster rate: 710 workers could have built the earthen bank in 0.6 days, 1,000 workers could have excavated and laid the foundations in 2.7 days, and the wall could have been constructed by 140 persons working for 1.8 days rising to 335 workers for 2.2 days with an additional 145 workers for a further 2.7 days to construct the wall (6.7 days in total). This means that a total of 2,190 workers could have constructed the entire length of the wall, excluding the v-shaped ditch, in 102 days or one third of a building season.

In addition to the construction figures, we need to add 221,402 person-days for the production of the materials, 26,964 cart-days and 8,706 boat-days (35,670 transport-days).[133] Assuming this is spread over the same number of years as the wall's construction (four seasons), this adds 205 workers to the work-force producing the materials plus 25 cart drivers, between 50 and 75 workers to manage the animals per day[134] and 24 sailors (based on a crew of 3 persons) working on 8 boats. This would bring the total labour force needed for the wall's construction to a minimum labour force of 531 workers over four years during the peak labour times.[135] If we assume an even more conservative timescale of eight years, the total labour force needed would be reduced further to only 266 workers based on the above estimates.

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[133] The total estimated here is 303,824 person-days, which is 116,176 fewer person-days than the total man-power requirements suggested by Elliott (2017, 86) of 420,000 person-days. He used the estimate of 35,000 m^3 of ragstone by Hall and Merrifield (1986, 28) needed for the blocks of the inner and outer facing and rubble core of the wall. Elliott based his labour figures on the person-days/m^3 rate proposed by Pearson (1999, 102) to build the wall circuit at Pevensey (Pers. comm. Simon Elliott 02.03.2019). Our figures would suggest the total proposed by Elliott to be too high.

[134] Every 2–3 animals needed 1 person to manage them. The range of individuals needed to manage the animals assumes a cart drawn by 6 oxen or 8 horse/mules (i.e. 2 workers per ox-cart and 3 workers per horse/mule-cart).

[135] This includes the lowest number of people needed to manage the animals used for cart-transport.

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