A targeted investigation of the historic carpentry of the Central Roof of the nave of St Pauls Cathedral

City of London

Standing Building Survey Report

November 2013

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A targeted investigation of the historic carpentry of the Central Roof of the nave of St Pauls Cathedral

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Site Code SPR13

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28 November 2013

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Summary

This report sets out to provide a full summary of the form of the timber roof framing of the central nave roof of St Pauls cathedral as part of the on-going research into the historic structure of St Pauls cathedral.

A new investigation including; targeted recording of two sample roof trusses and other carpentry details, such as the species and character of the timber used, and evidence for working methods, fastenings and the jointing used was commissioned from MOLA by Dr J. Schofield, Cathedral Archaeologist. It was also an aim to make brief records of reused elements and traces of repair. The investigation on-site was carried out by a small MOLA team, in conjunction with J. Schofield. Accurate measurements were made alongside other records including many photographs and this report aims to provide a detailed summary of the results of that work. It also includes a brief summary of the development of studies into historic timber frame carpentry, a short account of earlier investigations and also provides some interpretive analysis of the evidence recorded, taking account of some of its wider meaning.

1 Introduction and aims of this report

This report sets out to provide a full summary of the form of the timber roof framing of the central nave roof of St Pauls cathedral. Whilst many Londoners and visitors are very familiar with the distinctive external and internal form and character of this iconic structure, designed by Cristopher Wren, the carpentry of the roofs is largely hidden and little known. Indeed, this huge western roof of the cathedral, invisible to all public visitors, has not been subject to any detailed archaeological investigation and recording since brief visits made about 30 years ago. Since that time there have been significant advances in our understanding of historic timber frame carpentry and related fields such that a further investigation has been fully warranted.

As part of the on-going research into the historic structure of St Pauls cathedral, Dr J. Schofield, Cathedral Archaeologist, commissioned MOLA to carry out a new investigation including; targeted recording of two sample roof trusses and other carpentry details, such as the species and character of the timber used, and evidence for working methods, fastenings and the jointing used. It was also an aim to make brief records of reused elements and traces of repair. The investigation on-site was carried out by a small MOLA team, in conjunction with J. Schofield. Accurate measurements were made alongside other records including many photographs and this report aims to provide a detailed summary of the results of that work. It also includes a brief summary of the development of studies into historic timber frame carpentry, a short account of earlier investigations and also provides some interpretive analysis of the evidence recorded, taking account of some of its wider meaning.

This report and associated field records, including photographs, will be added to the St Pauls Cathedral archives in due course, as well as providing text and illustrations to be extracted and edited into a planned published volume on the Wren cathedral, now being compiled by J. Schofield. There are very extensive historical and pictorial sources, such as the detailed surviving building accounts, will be reviewed so that the evidence summarized here can be used to deepen and enrich the already known, long and complex story of building the cathedral. This great building project spread over the period 1668 to 1708, including early site clearance work with 33 years in total building time (Saunders 2001, 78). This followed the catastrophic destruction of most of the medieval structure on the same site. It was not a 'rebuild' and did not even follow the foot print of the earlier structure. Even though there were some documented efforts to temporarily reuse parts of the medieval structure and '…parcels of good oaken timber....' were acquired for roof framing (Schofield 2011, 218). These efforts were short lived, and a small, temporary chapel or 'tabernacle' was set up alongside the space for the new building. No timbers from the medieval or 16th century phases of work at the cathedral were found during this phase of archaeological work although some earlier stone work has been found reused (Schofield 2011, 222).

At this stage it must be acknowledged, that although the investigations were detailed and revealed much new information, they were also brief and with such a large structure as the nave central roof (continued west over the portico) it is possible that some more inaccessible and less obvious evidence may still remain to be discovered. It is also clear that a great deal of the work of the, up to, 400 carpenters that worked at St Pauls is not evidenced in the surviving structure, as it comprised the making of temporary form work and scaffolding for the masons, bricklayers and carvers. Indeed, few consider the contribution of the carpenters to this national building project in comparison to the better published timber roof craftsmanship evidence in medieval cathedrals such as Salisbury. It is hoped that this small study goes some way to redress this imbalance and demonstrates the possible insights that could be gained from similar investigations of other carpentry in the cathedral such as the great dome, choir, and transept roofs.

It is taken as read here that although Wren was the cathedral's key architect and had a project management role over much of its building, he did not actually build it himself. His personal recognition of the contribution of the, largely unsung, craftsmen whose labour and skills translated his graphic ideas into the reality we see now, is demonstrated by the fact that the final ceremony at the completion of the lantern on the great dome was for the craftsmen and labourers not the great and good of the City (Saunders 2001, 89).

2 Some key developments in the study of, historic English timber frame carpentry, and the nature of the raw materials and methods used

2.1 Some definitions and developments in woodworking trades demarcation

Whilst space does not permit a full description of developments in this large field in the last 30 years a brief outline is key to allow the full understanding of the many of the carpentry details recognised and recorded during this recent investigation. Whilst the term 'carpentry' is rather loosely used today, covering what were once many types of distinct woodworking trades, it still had a fairly precise meaning in 17th century England. Specifically, following late medieval practice, carpenters were principally responsible for structural woodwork used in buildings, bridges, docks and related structures. They also made temporary structures such as form work for masons and brick layers and the scaffolding used by all building craftsmen and labourers on a large building. In the permanent work their key specialism was the prefabrication of accurately made timber frames, which in mainly masonry and brick structures such as St Pauls, were mostly to be found in the roofs. They were also much involved in laying floor frames. The roof framing in St Pauls, and all historic standing buildings in England, was made using carefully carried out prefabrication methods (Harris 1979). These processes involved the making of accurate two dimensional frame units, such as wall and floor frames but in our case, just a roof frame made up of trusses set on a wall plate frame. Of course these frames were made from hand shaped timbers cut from, often somewhat irregularly shaped, trees. The conversion of these naturally irregular elements into regular standardized forms as far as possible was a key part of the 'mysteries' of carpentry. The individual flat frames also had to be accurately joined to other frames to make three dimensional structures. Each individual frame was laid out and worked on horizontally first even if it was to be vertical in use. The uppermost marked face of a frame is often now called the 'upper face' and will normally be the most informative face to record in detail (Harris 1979).

Archaeological evidence shows that timber frame carpentry was adopted in the London region starting around 1180 AD and by *c.*1230, the earlier timber building techniques had been superseded by the new 'carpentry' for any substantial structures (Milne 1992, Goodburn 1999). Although apparently brought to England from, SW France as the dating and even surviving terminology shows (eg. 'mortise and tenon', 'carpentry' etc.), distinctively English traditions of carpentry work gradually developed, alongside other distinct woodworking crafts such as ship building, coopering (stave built vessel making) and joinery etc. However, both details of surviving building fabric and documentary sources from the 17th and 18th centuries show that the demarcation zone between carpentry and the work of joiners was breaking down. Joiners traditionally made windows, panelling, cupboards, panelled doors and similar building elements, but documents clearly show after the Great Fire some individuals worked in both trades (Yeomans 1989, 38). Presumably this resulted from the very unusual conditions and huge demand for skilled crafts men in late 17th century London. It is clear that some traits more commonly used by joiners were widely used in the carpentry of the nave aisle roofs at St Pauls for example. The roof timbers there had been prepared as those used in joinery by finishing with extensive planning and moulding after conversion by sawing and hewing.

2.2 Some key developments in the practical study of historic carpentry in England, in brief

The most important pioneer in the practical study of historic carpentry was the late Cecil Hewett who carried out detailed sketch surveys of the carpentry of large numbers of historic buildings in the 1960's and 70's. This work included visits to examine many church and cathedral roofs. During this long campaign of recording he made a brief visit to St Paul's cathedral and was able to sketch the form of two of the types of roof trusses of the central nave and portico roof examined here (Hewett 1980, 248 and 1985, 69). His main interests were the general form of the frames, and the general form of the varied joints used but he also recorded some other details, such as mouldings and fastenings with sketches. He was also one of the first to realise that some of the surviving English carpentry was of great age. Indeed, apart from using historical dating he was also able to obtain some radio carbon dates. Apart from detailed sketches, he also produced paintings and models of some structures (It might be possible that he did this for parts of St Pauls).

Although his work was seminal it gradually became apparent to workers in the field that there were also other areas worthy of study and recording through precise detailed drawing, photography and close observation of well-preserved building timbers. It is also clear that there is some confusion of dimensions and misleading information of carpentry details in parts of his summary presentation of the St Pauls roof carpentry, such as the implied use of 50 ft beams in the central nave roof and erroneous details of the use of iron plates to reinforce tie beam scarf joints. However here we must note that by the time more detailed account of what he had sketched was published he had suffered a stroke and communication with his assistant was difficult (that assistant, A. Gibson, has also died, so checking details of what C Hewett recorded concerning St Pauls roof carpentry may now be impossible).

Though there are many specialist investigators of historic buildings who are still developing the field, one that stands out is Richard Harris of Avoncroft and then the Weald and Downland Open Air Museums. He was able to develop a more 'forensic' detailed approach to recording and analysing historic carpentry, working alongside skilled carpenters such as Roger Champion of the Weald and Downland Museum. New insights were gradually developed into the varying methods carpenters used for their work; 'how did they actually do that?' questions were asked in depth for the first time. Tree-ring dating also started to be used more regularly in investigations of historic buildings to provide a dating framework independent of dating by architectural style and limited historical records. Running parallel to these investigations systematic recording and dating work on medieval London waterfront structures was also beginning to provide more information (Milne and Milne 1982).

2.3 Documenting the form and size of trees used in historic carpentry

At the same time practical research by woodland botanist and historian Oliver Rackham, showed that building carpentry included much solid evidence for variation and change in the nature of England's historic wooded landscape. Prior to his work views of historic wooded English landscapes were dominated by poetic imagination and a small number of, possibly idealised, early paintings. Using close observations of the species, form and size of timber and round wood (small stems under *c.* 150mm diameter), in standing buildings, alongside documentary and map evidence a much more detailed picture of the changing nature of trees in parts of the English landscape was revealed (Rackham 1976, 1980). He was also able to outline some general trends and define distinct types of historic tree covered landscapes and management systems, all dating to before modern forestry methods took hold. The wooded land was termed 'tree land' and included many variants from wildwood extinct in England by the mid-13th century, to managed, usually fenced, 'coppice with standards' woods, and systems of growing trees in more open settings such as standard trees in hedgerows, or set in pasture land. He showed that in the 17th century, by the standards of most of Europe, England had relatively little wooded land. Most of the tree land was very intensively managed with fuel being a key product, later to be superseded by coal. These long established practices of English 'woodmanship' were not primarily focussed to produce tall straight trees as were the new continental 'forestry' systems being promoted in England by figures such as John Evelyn, a friend of Christopher Wren.

Rackham outlined a general and important change to the greater use of larger girth open grown oak and elm trees of modest height in the post medieval period. These provided logs which were subdivided into smaller sections for use. In high medieval timber frames the vast majority of oaks and elms used were typically smaller, woodland standards used as whole logs or baulks sawn into two. He also documented some particularly large timbers found in standing high status buildings. The largest timbers he found of medieval date were in the mid-14th century Octagon of Ely cathedral, these were tapered around 13″ (330mm) square but tapered as they reached towards the top of the parent tree and several had a total length of 40 ft. (c.12.15m). However, he cites a documentary source suggesting that oak timbers up to 50 feet long were 'in store at Westminster in 1329' (Rackham 1976, 75).

2.4 Pushing the detailed study of historic carpentry forward over the last two decades

From the late 1980's the first named writer has been able to contribute to systematic investigation, recording and analysis of historic carpentry found on waterfront excavations in the London region, covering the late medieval to mid-19th century period (and earlier.). It has been possible to bring knowledge gained, from work as a modern waterfront carpenter and practical experimenter in historic woodworking, to bear on the material evidence. This combined with increasing use of tree-ring studies has further developed the forensic study of changing carpentry in the London region (eg. Goodburn 1992, Goodburn and Minkin 2002 and Goodburn 2009). It has been possible to reconstruct many aspects of the building process as it relates to the carpentry from the standing trees through the making of the timber elements (timber conversion) to the finishing and repair of standing frames. Tool kits, methods of timber conversion and aspects of the logistics of building in timber have also been studied.

It has also been possible to carry out some targeted investigations of carpentry in standing buildings of the 17th and early 18th centuries, such as roof and wall frames of the 1680's and 90's at Middle Temple Inns of Court, although these and other detailed results are currently only available as draft archive reports (eg. Goodburn and Minkin 1996 un pub, MTE96 Report). Both the underground and standing building recording has together provide a large corpus of comparative evidence with which to compare the results of the investigations carried out in the St Pauls nave roof. Directly relevant features such as the early use of wrought iron straps and bolts to supplement the strength of timber to timber jointing is documented at a number of post-medieval sites from as early as the 1580's (Goodburn 2001). Another important documented feature of post-medieval London area carpentry recorded is the widespread use of, often long regular, conifer timbers ('softwood'). This appears to have been mainly Norwegian 'Scots pine' (Pinus sylvestris...) which was often then called 'fir' in the late 17th century building documents (Yeomans 1989, 41, Goodburn 2009. Although known in London Carpentry from as early as the mid-16th century it did not become commonplace till after the Great Fire when the Norwegians are said to have "warmed their hands on the fire of London". The lack of use of this new, and in many ways very suitable material, in the long span St Pauls nave roof is in many surprising and is addressed below.

Finally, from the mid 1990's onward collaboration between some historic building investigators and some of the new wave of timber frame carpenters conserving and often re-erecting historic buildings again pushed this aspect of historic building studies further forward. Key figures in this investigative work have been timber framers Joe Thompson, Paul Price, Henry Russell, Peter McCurdy and all have worked with R. Harris and R Champion at the Weald and Downland Museum. The first named writer has benefited from informal discussions with all of those craftsmen and attending a timber framing course lead by P Price several years ago. The subtlety of their mostly un published observations of historic carpentry practice is often surprising and relates directly to some of the detailed evidence recorded during this project in the St Pauls Nave central roof. For example, we can now be sure that most, if not all, historic carpenters in England used distinctive, but often faint, marks to indicate reference points for setting up their frames level so sets of joints could be accurately cut (Miles and Russell 1995). This was essential as the hand converted timbers often had surfaces that were not completely straight and level, even flat sawn faces would often start to distort as soon as they had been sawn due to inherent stresses in the timber. The often slightly irregular home grown logs of oak and elm were particularly prone to having irregular surfaces. In London we have now recorded a number of examples of post-medieval carpenters marks of this type which appear to have been most commonly made in the form of a fine scratched ('scribed') arrow which has now also been found at St Pauls (see below).

It is worth noting here that no carpenters' marks had apparently been recorded in any of the St Pauls roof carpentry prior to our recent investigation (J Schofield pers. com.).

2.5 Competing demands for very large oak timbers during the late 17th century

Of course naval demands for large, high quality oak timber were extensively documented over the period that the St Pauls roofs were being built and surviving correspondence shows that Wren was well aware of this issue (Yeomans 1989, 42). This must have been a factor in the documented difficulties in obtaining the very large oak tie beam timbers in particular as archaeological recording of reused naval timbers found in recent Thames side shipyard excavations, shows us that the timbers would have been ideal for making ship keels and other long strength members in the large ocean going ships of the period (Heard and Goodburn 2000).

3 Previous recording of the St Pauls nave central roof carpentry

The earliest records of the timber roof structure of the St Pauls central nave roof available to the MOLA team were fair copies of two drawings provided by J. Schofield from the St Paul's archives. The first used here is labelled the 'Poley Plan' which is a quite detailed scale plan of the cathedral roofs showing 'cutaway areas' where the locations of the nave central roof trusses are shown. This early 20th century plan has been used a base reference plan for recording here and from the limited measurements made during the September 2013 investigations it seems broadly accurate. The relevant section of this plan has been scanned and a version of it used for Figures 1, 8, and 9 in this report.

The other early drawing is an elevation of one of the cranked roof trusses over the western dome of the central nave roof (Apparently either Truss 16 or 17). This drawing shows the general features of the trusses which had tie beams cranked up to clear the large western dome but fails to show the jointing details, or fine carpentry evidence correctly. Also the tie beam ends are shown as flush with the upper face of the wall plate timbers which is inaccurate and would not have allowed for the necessary lap jointing. The distinctive expansion of the lower ends of the rafters is also not indicated. It was drawn at a scale of half inch to one foot by the Surveyors Office of St Pauls cathedral (Apparently in 1927 J Schofield pers. com.). Interestingly this drawing does not show the small vertical timber struts now wedged between the cranked tie beams and low collar beams (See Fig.3).

Dating from the 1970s we have rather more detailed published drawings made by the historic carpentry recording pioneer Cecil Hewett (Hewett 1980, and 1985). These were reworked from detailed sketches made on site in the 1970's. The published drawings show the general form of the horizontal, single piece tie beam trusses of the eastern part of the nave central roof and also the cranked tie beam trusses used in the western portico end. However, these drawings are not too scale and several substantial details are not shown such as the thickening of the basal ends of the rafters and king posts even though the angle of view would have allowed that to be indicated. The lack of scale recording must also have lead him to suggest lengths of '50 ft' for the great tie beams of the roof which is noticeably longer than they actually are (Hewett 1980, 248). Though the general form of the main jointing of the roof trusses, common purlins, and wall plate scarfs are shown in outline there are also smaller errors here and in the depiction of the iron reinforcements of the joints. It is clear that the published drawings must have been worked up from rapidly made sketches done on site probably in poor light. No fine carpentry mark or tool mark details were indicated but this was not apparently part of Hewett's recording aims for any buildings he visited. We must note that he appears to have had little time and only poor lighting in any case, and problems of communication after having a stroke also appear to have had an effect on the accuracy of the final communication of the details recorded. However, it is plain that his 1970's recording of some carpentry details of the great roof, and indeed other parts of the St Paul's roofs advanced knowledge significantly at the time.

He also appears to have been able to see details we could not access in September 2013 as he was able to sketch the form of the jointing between the tie beam ends and the wall plates which he shows as a lap dovetail, a commonly used joint for this purpose in English timber frame carpentry (Hewett 1985, p69, fig 64). Importantly on the same page in which a slightly inaccurate interpretation of the crude St Paul's nave roof, tie beam scarf is shown a stronger 'counter cogged and forelock bolted' scarf of similar dating is also shown (Hewett 1985, p224). The latter scarf resembles scarfs used in large ship deck beams of the period.

Hewett's wide knowledge of historic roof carpentry also allowed him to suggest that the unusual common purlin form found in the nave and choir roofs had many parallels in the early surviving roofs of New England.

4 The methodology and nature of the site recording carried out by the MOLA team in the central nave roof at St Pauls September 2013

4.1 An initial walk over visit early in 2013

The MOLA team's involvement with investigations of St Paul's roof carpentry was initiated by a short visit of DMG and AC lead by J. Schofield and members of the St Pauls staff, early in January 2013. This was a very brief visit with modest lighting available, totalling about 1.5 hrs. and covering the nave and choir central roofs as well as other areas. However, the survival of several unrecorded features of the roof carpentry were very briefly noted at that time, such as carpenters joint and truss numbers, curious multiple, rope wear marks (then not understood), some finer carpenters joint lay out marks, and repairs following bomb damage in the choir roof. This initial visit enabled the drawing up of a more specific brief for the longer targeted recording visit carried out later and limited to the nave central roof.

4.2 The main site visit to carry out the targeted investigation and recording of the roof carpentry of the central nave roof

The MOLA investigation and recording team was guided to the nave central roof space on the 26th of September 2013 and the investigation and recording took place between *c.* 9. 30am and 4.30 pm when the team had to leave due to the beginning of evensong. The MOLA team comprised the Archaeological Woodwork Specialist D. Goodburn (main author of this report), Senior Archaeological Photographer A.Chopping, Standing Building Archaeologist, A. Karim, and Archaeologist T. Standfield.

The main aim was to make a high quality general photographic record using powerful lighting. Alongside this two different representative roof trusses were selected for detailed recording (Trusses 4 in the east and 15 to the west). This was carried out with the use of a set of steps that could be carried up through the very narrow access routes. However, the very top of the trusses could not be examined very closely due to the height of the steps, though they were observed in powerful light, photographed and measured using a disto (electronic measuring device). The key records comprised carefully annotated sketches with detailed measurements with tape measures and a distometer, wherever possible, backed up with rapid snap photographs with scales. In addition to features revealed by the general photography lighting, details were highlighted using low angle torch light. Many other fine carpentry details were also recorded by measured sketching of Truss 1. Later a walk over with small additional lights was carried out, to note the form and location of carpenters truss and joint marks as well as a number of other features; these observations were located by reference to the trusses numbered by J Schofield. Here we referred to copies of the Poley roof plan and also annotated these. Finally, several locations worthy of high quality photography of fine carpenter's marks, accessible joint details and several tool marked surfaces were selected. Initially 1.5 days were allocated for this work but in practice only one day was facilitated and although much new information was recorded it is clear that some additional details might be revealed by a further short visit, particularly to the less accessible western end of the roof also known as the 'portico roof' (to be confirmed).

Following the day on-site in the nave central roof, the records made were listed, photocopied and the two main truss drawings worked up to scale as digital drawings, (very largely by AK). Other drawings were also created and turned into digital scale versions, using AutoCAD. The draft drawings were then reviewed with the site notes and key digital photographs taken by AC and further amended. Both the original site paper records, digital drawings and photographs are the archive record of this work together with the final draft of this text. Full digital and hard copies of all this material will be passed to J Schofield and the cathedral archives in due course.

5 Description and discussion of the St Pauls nave, central roof and portico roof framing

5.1 The general lay out and form

Readers are referred to Figure 1 that is derived from part of the Poley roof plan annotated by J Schofield, with the trusses numbered from 1 at the eastern end to 25 at the western end of the portico, which is in fact a continuation of the nave roof. The roof is of a 'common purlin' type in which multiple, light, longitudinal beams ('purlins') are supported by 24, very wide span, roof trusses. From Truss 14 westward the roof span widens and two modified forms of truss were used which are described below. It is the case that the use of multiple light purlins set on widely spaced heavy trusses, is typical of roof framing in historic buildings on the east side of the North Sea and in parts of the NE USA, but relatively uncommon in England. The system has some practical advantages with a roof of this huge scale, particularly as it was erected in stages over quite a period of time. The simply joined common purlins were lap jointed into the faces of the rafters, presumably after facing pairs of trusses were erected. They did not need to be fully framed in early in the prefabrication of the complete roof frame as would have been the more commonly found 'butt' or 'clasped purlins' etc. The fitting of the relatively light common purlins also allowed for slight adjustments to take account of irregularities in some of the very large oak timbers used (eg See rafter heads in Truss 4 Fig 2). Once this had been done in situ a flush, regular, outer surface was made for the nailing on of the pit sawn, oak 'sarking' planks that the lead outer cover was then laid on. No wind brace timbers were used but the combination of a modest pitch, robust trusses with closely set purlins, covered by vertically set sarking planks and a heavy sheet lead covering is clearly quite strong enough to resist racking strains imposed by several "100 year storms".

At the extreme west end a pair of, modest scantling, oak beams served as rafters ('Truss 25'), set on stone corbels protruding from the east face of the portico gable instead of a framed truss (Fig 1). Two half trusses (22a, and 22b) also exist now between trusses 22 and 23 but from the tool marks surviving on some of the timbers used these appear to be of 19th to early 20th century date (Possibly dating to known rebuilding work of c. 1903, J Schofield pers. com.). These additional trusses do also include some old oak second-hand timbers, at least one of which appears to derive from a common purlin roof somewhere else in the St Pauls structure (Possibly the bomb damaged choir roof?)

The roof trusses were evenly spaced *c.* 7 ft (2.2m) apart. The light multiple purlins and ridge piece beams were of pit sawn oak and varied slightly in cross section ('scantling') but centred on c. 130 mm (*c.* 5½″) deep and 110mm (*c.* 4½″) wide. When noting dimensions recorded now we must realise that the 'nominal' dimensions the green timber was marked out in would have been larger allowing, for what the seasoning shrinkage takes. The purlins were simply notched and housed in the top edges of the rafters. A set of 23 on each side of the roof in the eastern half of the nave central roof and 24 each side in the slightly, larger western trusses.

The roof framing and even much of the plank covering laid over the purlins is nearly all original, a testiment to the strength of the workmanship of the turn of the 18th century and the weather tightness of the lead sheet roof covering. It is also clear that the stone supporting walls are also in a robust condition having experienced little movement except for a small drift westward in part of the northern wall which has broken the scarf joint in the wall plate at one point.

The basic roof truss form comprises a king post and two diagonal struts jointed to the principal rafters. The king posts and rafters were also jointed to horizontal beams either tie beams or low collar beams (Figs 2 and 3). The pitch of the roof is moderate due to the highly waterproof nature of the lead covering. All the lower joints were also reinforced with bolted, wrought iron straps. However, the tie beam assemblies took three forms, each discussed separately below.

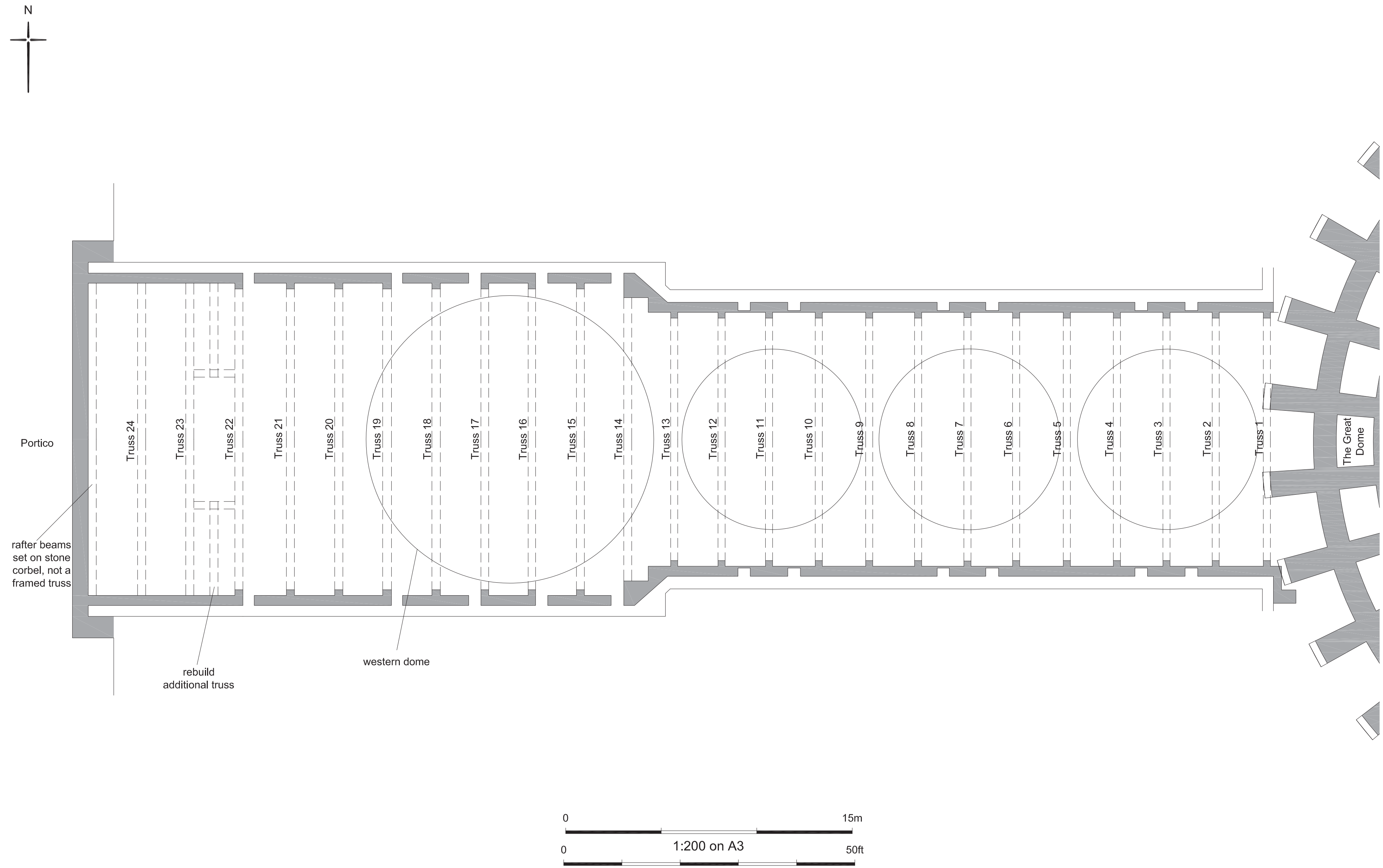

Fig 01 Copy of the Poley plan of the roof over the central, main roof of the nave of St Paul's cathedral.

5.2 The eastern roof trusses with single piece tie beams

The standard truss form used in the St Pauls nave central roof (Trusses 1-13) and the central or 'nave' roof of the choir to the east is a very large span, simple form of king post truss with two diagonal struts tenoned into, the foot of the king post and half way up the rafters. This can be said to be a typical form of roof truss for the period in London, apart from its scale, but there are also some features which appear distinctive to the larger St Pauls roofs. These are probably related to the sheer size of the roof structure. Both the lower ends of the rafters and king posts were made thicker by about 50mm on each face either out of the solid timber or by nailing on short sawn planks of oak as the individual parent oak log allowed. These 'jowl-like' features had the effect that the base of the timbers would have been strengthened and also provided for a fairly flush surface around which the wrought iron straps could be fitted. Uneven thicknesses of the joining timbers would have made the job of fitting the iron reinforcing straps far more difficult. The rafters were also diminished in depth above the point of jointing with the diagonal struts (Fig 2). This existence of these changes in dimensions shows that the master carpenters, probably Longland, were intimately engaged in marking out the timber for the sawyers. Only the struts from the king posts, common purlins and oak sarking boards could have been bought as standardized items sawn out without close supervision of one of the senior carpenters. It also seems likely that those in charge of the marking out had some form of diagrammatic or detailed written record of where the various expansions of dimensions needed to be in the finished timbers.

The dimensions of several of the long and relatively straight tie beams were measured and were found vary a little but were generally c 430-450mm (16½″- 18″) deep at their largest end tapering down to c. 370-350mm (14¾″- 14″) deep at the other end, cut from higher up in the parent oak. They were also a little less deep over the middle section that is each end thickened a little to allow for the jointing in of the rafter feet. The beams varied a little in thickness but were c. 280mm to 300mm (*c.* 11¼″-12″) wide E-W) and *c.* 14.08m (46′ 2½″) long. The length fits the building accounts evidence where a length of '47 ft' is specified by Wren for the very long oak beams sourced from the Duke of Newcastle's estate (As Wren's measuring stick used for checking work survives it would be interesting to check its dimensions and find out whether it is marked in the same imperial ft distance we use now or not, a small discrepancy would be greatly amplified over 47 ft). The missing 9 1/2″ could be easily explained by a little shrinkage and the recutting of the beams to remove the extreme ends likely to be slightly split by drying 'shakes'. The 'scantling' or cross sectional dimensions, described in a Wren letter as ' 13 inches and 14 inches at the small end, growing thicker' (Above) are also close to those found in the surviving tie beam smaller ends allowing for a little shrinkage. That is, they were found to be around 14 inches or just over deep but were a little thinner now at *c.* 280 to a maximum of 300mm (11-12″). So here the recording shows that the master carpenters supervision of the preparation of these exceptionally large timbers paid off and fairly closely matched Wren's specifications.

The types of joints used in all the roof trusses could not be examined in detail in the central nave roof as all the carpentry seen was still fully assembled. However, the location of the oak locking pegs (26-28mm diameter), some surviving joint layout marks and the presence of small gaps that could be looked into with torches, allows the following description. The rafter feet joined the tie beam ends with an unusual form of shallow bridle joint combined with a 'birds mouth' type notch (Fig 2) rather than the common place chase mortice and tenon. It seems likely that this adaptation was made to allow easier assembly of the very large, heavy timbers and because the joint was always to be reinforced with a large, bolted, iron strap. Hewett was the first to note the presence of this unusual joint in the roof and illustrate it; we might only add that the notches used in the joint stand up a little more than he indicated providing a slightly greater ridge for the rafter feet to engage with. However, a fairly standardized double pegged mortice and tenon was used for the foot of the king posts and a single pegged mortise and tenon for each end of the king post to rafter struts. Unfortunately we could not closely access the joints of the rafter heads with the top of the king posts. The joints used were secured with two oak pegs each and are most likely a form of standard mortise and tenon, but we could not totally rule out the use of some form of bridle joint.

Extensive use was made of wrought iron bolted straps in the St Pauls nave and choir roofs, indeed they were clearly key original features of the design of the huge assemblies. Although the straps were forged to fairly standardized forms the length of the screw threaded bolts used to secure them varied considerably as if they included some originally made for another purpose. To make up the difference in the locations of the threaded sections, pierced iron packing pieces had been used under the heads of many of the nuts. In some cases this amounted to a nut and two packing pieces. We must be seeing elements of economy coming in here. The use of screw bolts instead of the earlier, wedge locked, 'forelock bolts' would have made the adjustment and tightening of the bolts, following the seasoning shrinkage in the timber, much easier.

The straps were broadly similar dimensions at *c.* 25-20mm thick by *c.* 100mm wide and of varying length to suit the locations. Those used at the junction of king posts and tie beams and those used to joint rafter feet to tie beam ends had an elongated 'U' shape and either two or three bolt holes (Figs, 2 and 3). Those used to fasten the western horizontal tie beam scarfs, and link the ends of the cranked divided tie beams were flat straps with dovetail ends and 6 or 4 bolt holes respectively. The use of these straps is shown on both faces of the scarfed, longer horizontal tie beams by Hewett but this is incorrect, indeed impossible as the upper strapping would have fouled the ends of joint with the king post. However, a few short straps have been noted on the opposing faces of the scarfed beams, such as that linking two bolts (35mm diameter) in Truss 14.

5.3 Some details of the sample eastern roof truss 4 (Figure 2)

Truss 4 is our illustrated sample truss and was a fairly typical example, although the tie beam was one of the straightest. It must also have been cut from a slightly larger tree than most as it had pit sawn faces extending from one end to the other and only a little sapwood on its outer corners at the S end which would have been uppermost in the parent tree (Fig.2). However, the tops of rafters were both cut out to follow a slight curve in the parent log and the common purlin joints adjusted accordingly to maintain a flush upper surface for the roof. The rafter feet had solid sawn 'jowls' on the eastern, upper face and added planks nailed on to thicken the western faces. Combined truss and joint numbers cut with a 2 inch chisel were found on the eastern face in the form of an 'X' with an extra 'tag' added on the N end. This was one of two forms of combined truss and joint numbers found in the central nave roof and different to those found on Truss 15 (Figs 2, 3 and 8 and see below). One feature only recognised on the north end of this tie beam east face was a strange obliquely augured hole of no obvious function, though its use as an attachment hole for a bar used in the hauling of the large beam or partly worked parent log might be a possible explanation. Oblique holes have been found in broadly similar large oak baulks of Roman date excavated from London at the Regis House waterfront site, and it was clearly the case that they were used for hauling out the timber there (Goodburn 1998 un pub and also tested experimentally with the BBC).

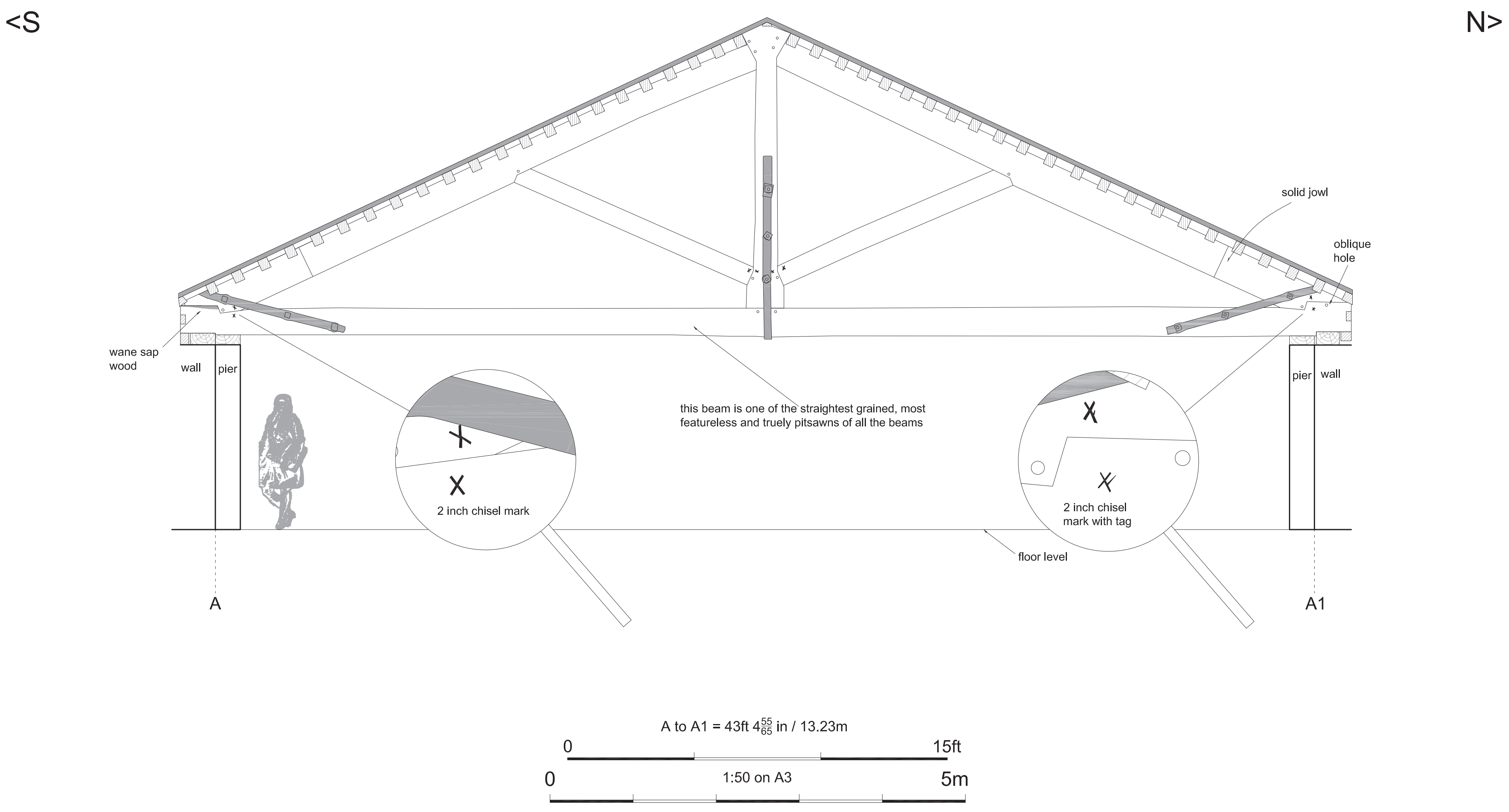

Fig 02 Elevation of the east face of Truss 4, main central roof of the nave of St Pauls cathedral, showing its form with a long, horizontal, single piece tie beam, King post, carpenters truss and joint numbers and original iron reinforcing straps.

5.4 The wall plates in brief

Except in the western edges of Britain, such as in late medieval Torre Abbey, the junction of wall and roof includes a longitudinal beam usually termed a 'wall plate'. This is the case in timber framed, masonry, brick and earth walled buildings. In the case of the central nave roof the wall plates into which the ends of the tie beams of each truss were jointed were of quite modest proportions, presumably because the beams were well supported by a robust masonry wall, at least when the roof was completed (See below). The north and south line of wall plates were made of pit sawn beams *c.* 300mm wide and 150mm deep (12″ x 6″). They appeared to have been cut out of roughly half a medium sized log i.e. 'box halved'. The beams making up the long plate were joined with a form of bridled scarf in which the tongue of the bridle is secured with in the joint and secured with two pegs. The form of the joint used where the ends of the tie beam engaged with the wall plate was hidden from the investigating team but we can say that it must have been a shallow lap joint of some form as the tie beam soffits (lower faces) are recessed by *c.* 20-25mm (1″). Hewett illustrates this joint as a shallow lap dovetail which was one of a series of common forms for such a joint during the period. But how he was able to see this detail is quite unclear, though it is entirely plausible.

The loading at the point where the rafters joined the wall plates was spread by using small oak plank pads on masonry piers projecting inwards from the main wall line and a second oak longitudinal beam, or pseudo wall plate, level with the outer end of the tie beams (Fig.2). The wall plate and pier support system was the same in both the eastern and wider western parts of the roof.

5.5 The western roof trusses with canted up jointed tie beams over the western dome

Here we shall only describe the areas of difference between these trusses and the 'standard' wide span St Paul's roof truss described above. Clearly the main difference is the use of a divided tie beam cranked up to a large low collar beam joining the rafters about $^{2}/_{3}$rds of the way down their length (Fig. 3). The change in roof truss design was essential to allow space for the building of the larger domed vaulting designed by Wren at these points. Interestingly, the small vertical struts now wedged between the tie beams and collars are not shown on the 1927 dated St Pauls Surveyors Office roof truss elevation. This, together with their irregularity and variation in patina, suggests they are recent additions. The lower ends of the rafters in this form of truss were also expanded in thickness towards the base, as in those of the eastern sector of the roof, but the expansion occurs almost half way up just above the collars (eg on the east, 'lower' face of Truss 15).

The jointing was found to be of same general form as that used in the eastern trusses but with double pegged mortice and tennon joints for the ends of the collar beams and long double pegged, chase tenons for the upper ends of the cranked up tie beams. The inner ends of these cranked up tie-beams also press against a small oak fillet block set under the collar beam and held in place by the iron strap used at that point to firmly fasten the king post. The carpenters also fitted a pair of wrought iron straps linking the heads of the paired tie beams to resist spreading strains. This strap was forged with a dovetail end, four screw bolts and partially inset into the upper faces of the tie beam ends, presumably with the intention of increasingly holding power (Fig. 3).

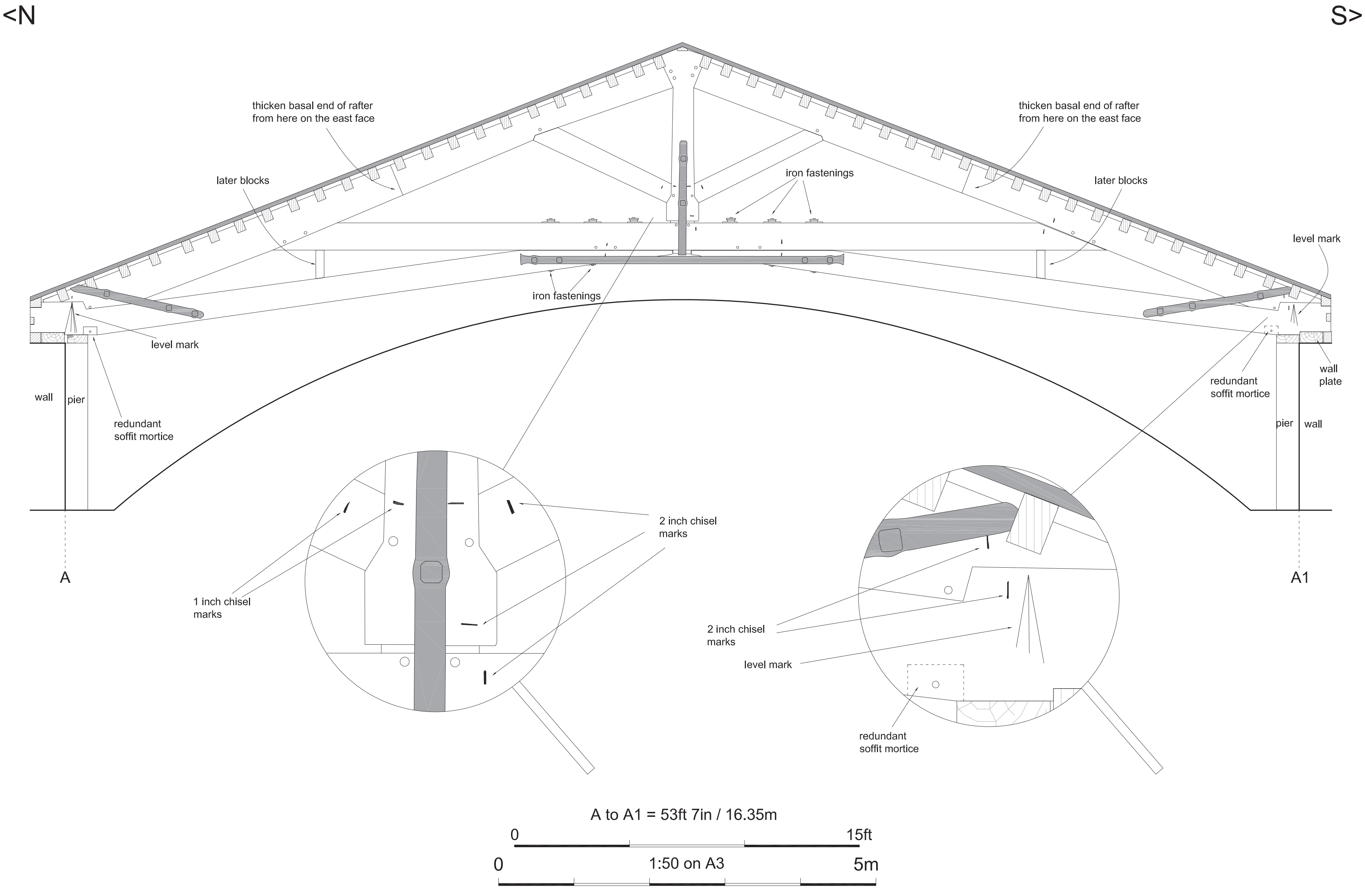

Fig 03 Elevation of the west face of Truss 15, above western dome, main roof of St Pauls cathedral nave, showings its form with a divided tie beam canted up to a low collar and king post assembly, carpenters marks, and original iron reinforcing.

The upper ends of each divided tie-beam were also secured to the collar beam with three threaded iron bolts (see Fig 3). Although the full span of the western section of the roof is *c.* 17.29m (56′ 7″) the form of truss also allowed the use of much shorter, though still very large, timbers. The longest elements of these trusses are the low collar beams which have a length *c.*11.3m about 10′ shorter than the single piece tie beams of the standard St Pauls trusses. We might puzzle as to why this clear reduction in need for truly exceptional oak timber was not more widely specified by Wren, though the form of the trusses described below do indicate that, in a sense, reason eventually triumphed over tradition and prestige, as from this point westward no single piece tie beams were used again!

5.6 Some specific details of sample cranked truss 15

The recorded sample truss of this form was Truss 15 which appeared to be typical of the form and was the most accessible. The truss comprised eight principal timbers all cut from whole logs by pit sawing. The timbers were fairly neatly converted and fairly straight grained but had some medium sized knots. The paired tie beams had maximum dimensions of c 450mm (18″) deep by 280-290mm (11¼ - 11$^{5}/_{8}$″) thick, the rafters a maximum of 380mm (15½″) deep by 270mm (10¾″) thick. The post is 300mm (12″) wide by 275mm (11″) thick, the collar 360mm (c. 14½″) deep by *c.* 290mm (11$^{5}/_{8}$″) thick and the struts *c.* 250mm (10″) deep by (8″) 200mm thick.

The ‘upper face’ of the truss, which is now the western face, showed several carpentry marks of interest such as arrow form level marks scribed in the tie beam ends, and a set of chiselled I combined joint and truss numbers. The ‘I’ was cut with a smaller chisel on the N side of the truss and a 2″ chisel on the south side (See below for more on the meaning of these marks). Another key feature of note seen on this truss and Trusses 16, 17 and 18 were redundant mortises cut in the soffits of the north and south ends of each tie beam pair, which was partially blocked by the underlying original piers and pier pads. Initially it was suggested by J Schofield that this might indicate evidence of previous use of the timbers. However, the uniformity of location, staining and joint layout marks suggest to the MOLA team a different explanation of wider importance for reconstructing how the upper parts of the nave were built (See below).

5.7 The western roof trusses with scarf jointed horizontal tie beams

The roof trusses with horizontal tie beams in the western part of the central nave roof were very similar to those of the eastern section of roof except that they were a little wider and had tie beams made of two timbers scarfed together. Whilst the use of two joined timbers rather than one huge, very difficult to find and transport, beam of oak seems entirely rational from a modern perspective, the form of scarf used seems very inappropriate. The maximum length of the longest timber in this form of truss was *c.* 10.41m still very large but nearly 4m less length than the single piece tie beams of the eastern trusses.

This joint was entirely dependent on the locking effect of the six through bolts used and to some limited extent the clumsily inset dovetail ended strap on the lower face. As these straps were only a loose fit this effect would have been minimal. It seems that Wren and his master carpenters were unaware of or possibly unwilling to use alternative forms of scarf joint that would have been more secure and required much less expensive iron to fasten. By the end of the 17th century shipwrights building very large ships had been using more elaborate, much stronger forms of bolted scarf joints in major cross beams for some years. In these joints ridges of timber were cut so as to interlock called ‘tabeling’ by shipwrights and ‘counter cogging’ in carpentry.

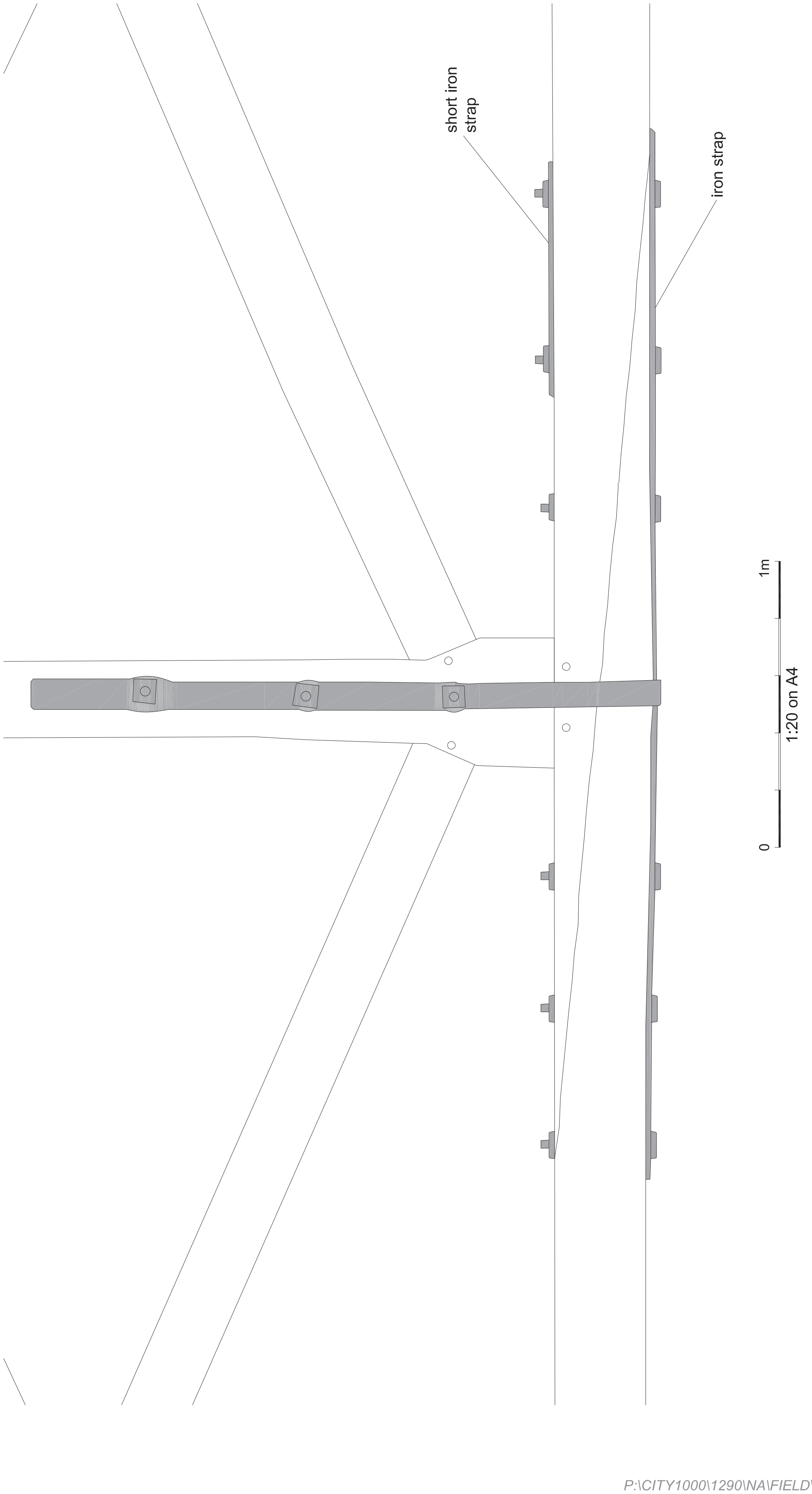

Fig 04 Drawing showing the form of scarfed horizontal tie-beam used in the wider western trusses

Fig 5 General photograph of the form of the horizontal tie beam roof trusses of St Pauls nave central roof looking east with Truss 14 in the foreground. Showing part of the through splayed bolted scarf in the, slightly wider, western, Truss 14 and the un-scarfed 14.08m (46' 2") long tie beams used in the eastern trusses. Also visible are the chisel cut, combined truss and joint numbers in 2" and 1" sizes.

A cogged type of scarf was found and sketched by Hewett, used in broadly contemporary carpentry in Westminster Abbey work which it seems likely that Wren or some of his team should have been aware of (Hewett 1985, p224). The very crude recent addition of unnecessary grey and black paint on the straps makes the appearance of this even uglier (Fig 13).

5.8 Changes in the nave roof pitch to clear the largest western dome

Where the roof widens a little in span, at the point at which the large western dome appears at Truss 14, it also rises up little (Fig. 6). This change in height is also associated with changing the angles of some of the diagonal struts, even in the horizontal tie beam trusses. The slight change in external roof line cannot be seen from the ground but is clearly visible on 'Google earth' aerial views of the cathedral.

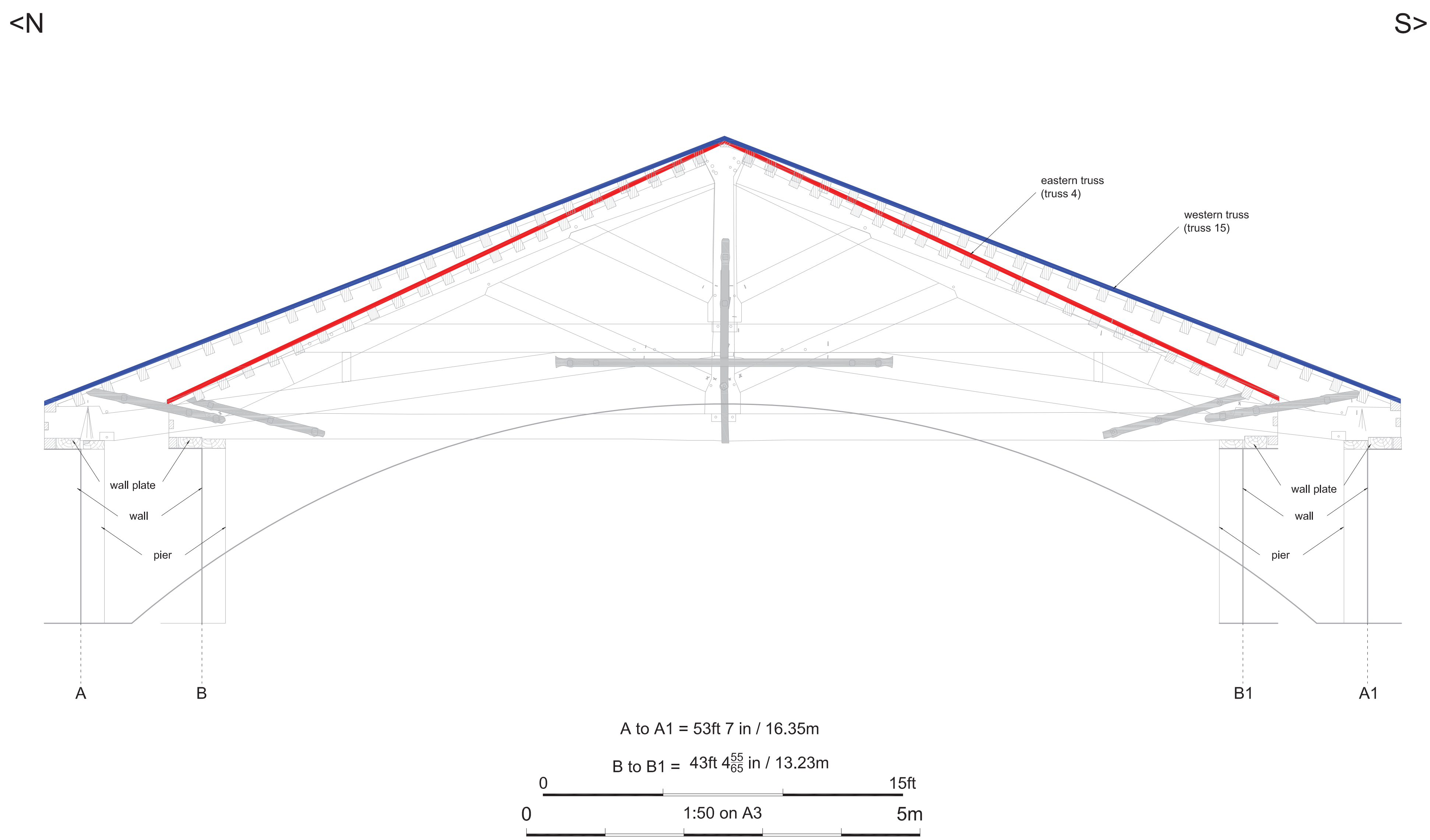

Fig 06 Drawing showing the merging of the outlines of the slightly higher western trusses and the lower eastern trusses

6 Some less obvious evidence of the St Pauls nave, central roof carpentry, part of the 'mysteries of carpentry' and requirements for assembling the frames

6.1 Combined truss and joint numbers

Figure 8 is a plan based on the Poley roof plan showing the numbered roof trusses and the location and style of the combined truss and joint numbers recorded. Many readers will be aware of the historic use of various forms of numbering, most commonly in versions of Roman numerals, to label particular joints in a timber frame. The key purpose of this was to enable individually cut male and female elements of joints to be refitted on-site after the prefabrication of a timber frame. Sometimes in post- medieval London these would be individual numbers for each joint but at other times they would simply be one mark repeated as the components from some frames could only be fitted together one way. This latter type of marking is called combined joint and truss marks here. In the case of the St Pauls central nave roof there were actually four similar elements, the pairs of rafters and the king post struts. We were able to find two different ways the master carpenters distinguished these to avoid attempts at erroneous trial fitting on site. One type found involved the use of versions of Roman numerals cut with 2 inch chisels including a small additional cut or 'tag' on one side of the truss (eg Truss 4 Fig2). The other form found involved the use of a 2″ chisel mark on one side of the truss and a 1″ or 1¼″ on the other side (eg Truss 15, Fig 3). The marks survived in over 90 % on the locations were they would have originally been used, although low angle torch light was needed to reveal the more abraded examples. This patterning in the evidence appears to reflect the supervision of two different master carpenters, and as we know of two named from the documentary sources, Longland and Jennings, it is likely that they were responsible. If we consider that Longland was paid for erecting eleven of the roof trusses of the nave roof in 1704' and that there are 11 trusses marked using the 2″ chisel and tag system, it seems very likely that those were made under the supervision of Longland. These trusses include Trusses 1,2,4,5,7,8,9,10,11,13, and 18, by default the other trusses marked using the other system are likely to have been made under the supervision of Jennings. It is very rare that the work of individual named master carpenters can be associated with the actual frames they supervised the making of rather than just being able to record that a particular carpenter worked on a building or roof.

It should be noted that the run of the numbers used by the master carpenters did not necessarily flow in a conventional sequence as might have been expected, neither was the marked upper face of the truss frames always orientated the same way it did not seem to have been important.

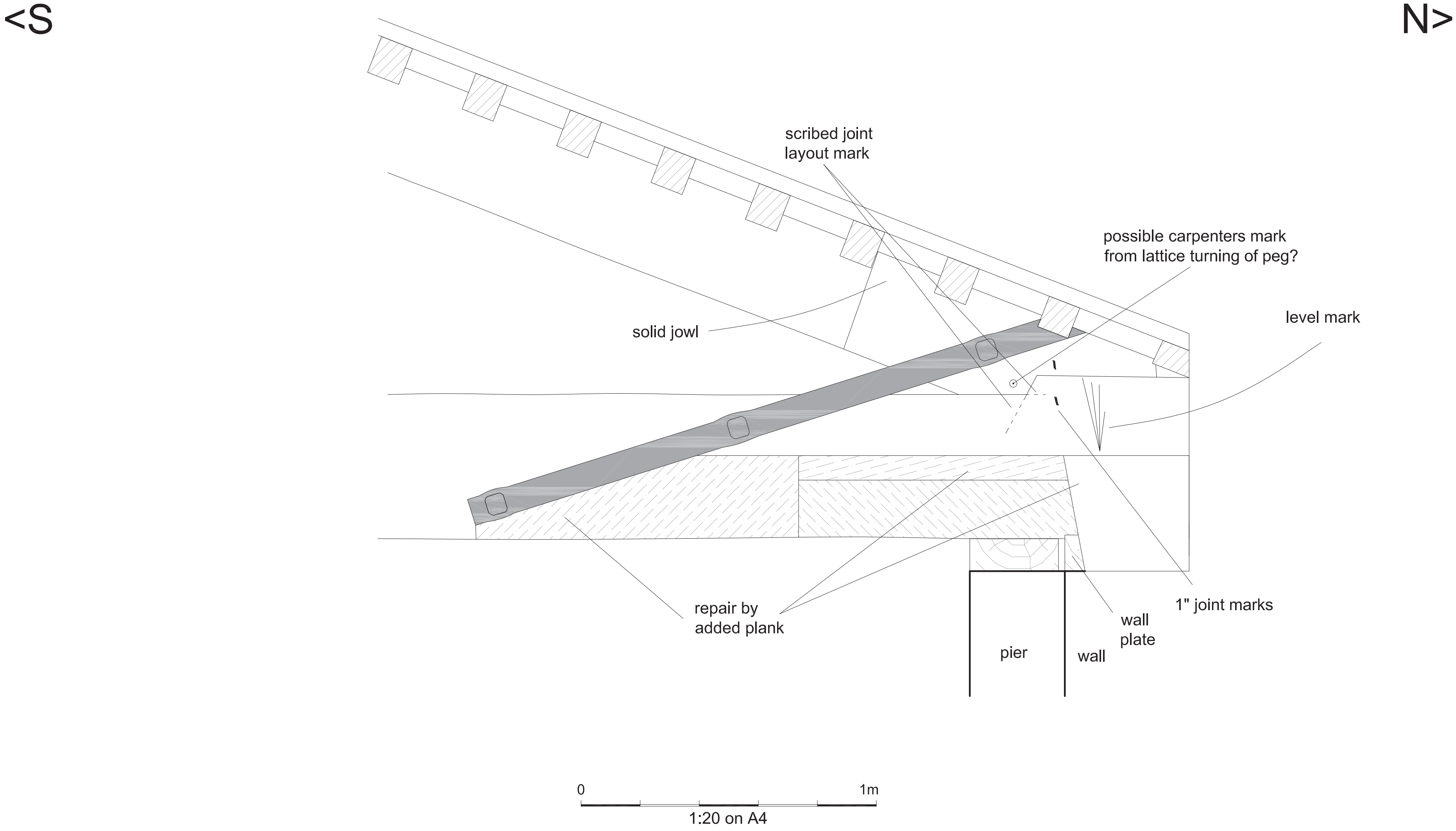

Fig 07 Detailed drawing showing the fine carpentry details surviving on the north end, east face, of Truss 1. The arrow shaped 'level' marks, scribed joint layout marks, chiselled combined truss and joint number marks and pit saw marks.

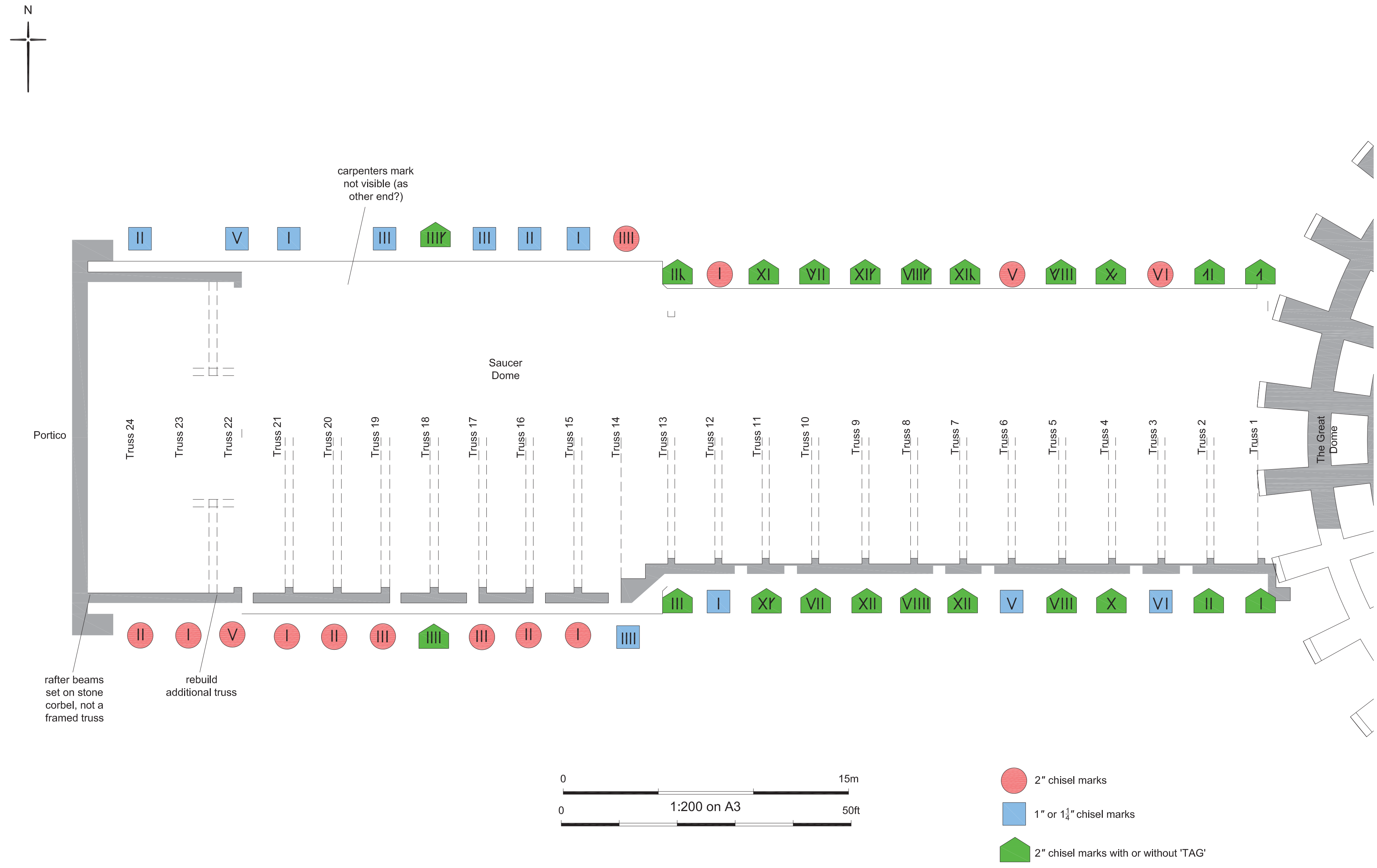

Fig 08 Outline roof plan of the main roof of St Pauls cathedral, based on the Poley plan, showing the locations and type of the carpenters combined truss and joint number marks, indicating a pattern of discontinuous work, almost certainly lead by the 2 different master carpenters, Longland and Jennings

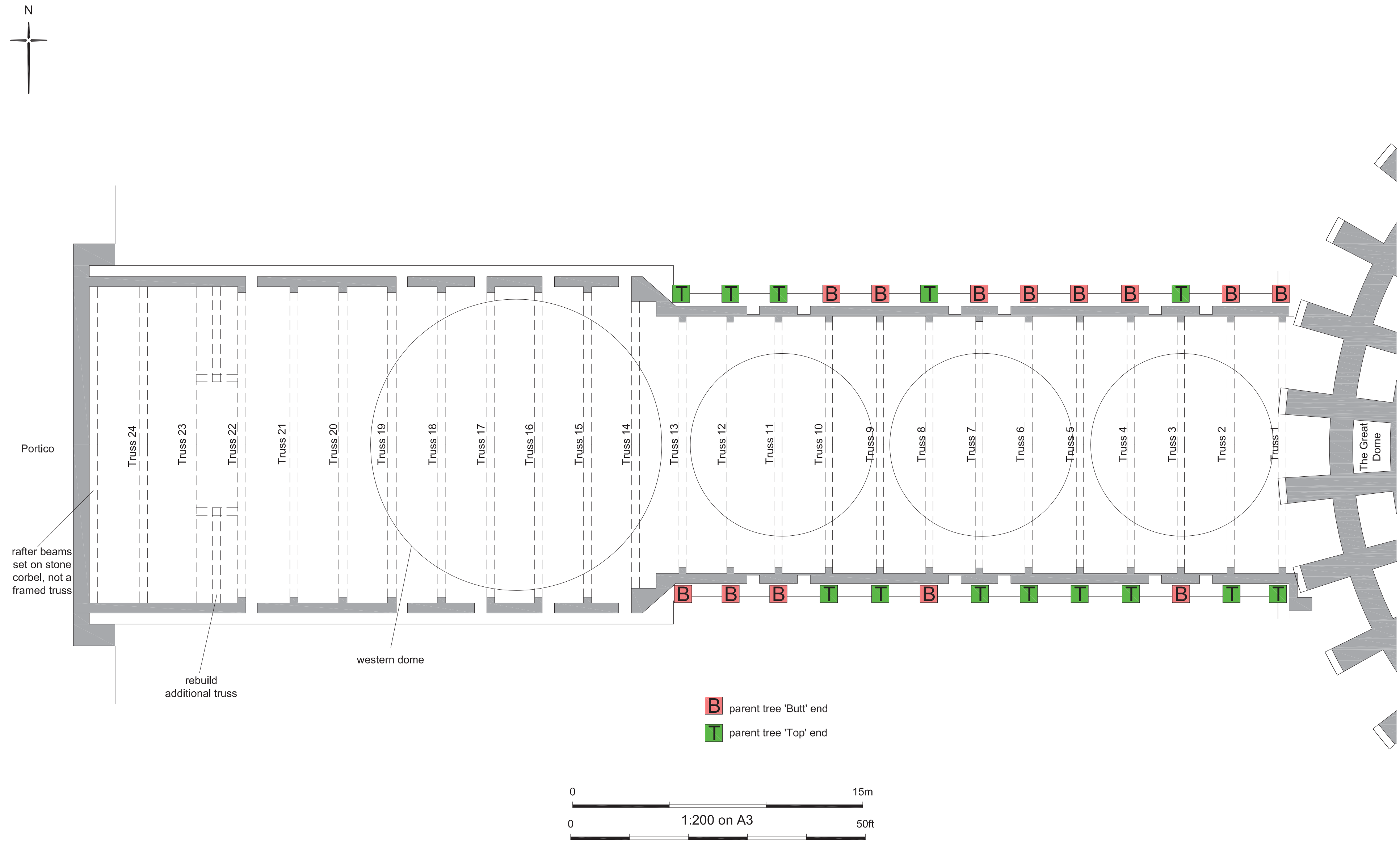

Fig 09 Outline roof plan of the main roof of St Pauls cathedral, based on the Poley plan, showing the locations of the ends of the tie beams close to the butt of the parent trees and the tops.

6.2 Level marks on the beam ends

As outlined in the introductory section above timber frame carpenters also had to use many fine and often hard to recognise reference marks which have only been identified over the last few years. These were normally made as fine scratched or 'scribed' marks. The carpenters would have made the roof trusses laid out horizontally on trestles or beams. To ensure the joints and timbers were aligned accurately even if the timbers were a little uneven, they had to be set up nominally level. Later the horizontal plane would of course become precisely vertical for the roof trusses. However, the tie beams were principal timbers also involved in the wall plate - tie beam frame. When they were set up for jointing into that frame the level marks would have been accurately checked for verticality. To set up a plumb level the surface of the timber had to be flat and fairly smooth so unevenness was sometimes trimmed off in the area used as the reference for levelling. Many of the tie beam ends in the central nave roof at St Pauls had surviving level marks in the form of faint scribed arrows, which were orientated up or down in the finished truss. The example presented here is that recorded at the N end of Truss 1 on the east face (Fig 7). In this case the pit sawn surface was clearly planed level and smooth before the arrow level mark was made.

6.3 Joint layout marks

Another essential feature of the methodology of timber framing is fine scribed lines used to mark the timbers for joint cutting. These types of marks survived in many places on the roof truss timbers but were very faint. Some of the clearest and most accessible were recorded around the redundant, tie beam soffit mortises of Trusses 15 -18 (Fig 7).

6.4 Evidence for the irregular alternation of the larger butt and smaller upper ends of the tie beams in the eastern trusses of the central nave roof

It is clear that the tie beams of the eastern trusses were so long that they had to be cut with a taper and Wren's correspondence (cited above) indicates that he was indeed specifying that detail. We might have reasonably expected that the deeper, heavier and stronger ends of the tie beams from near the butt of the parent tree would have been alternated from side to side along the length of the roof but Figure 9 shows that this is not the case. The placing of the butt ends of the tie beams was surprisingly, clearly arbitrary.

7 Reconstructing the great oaks used to make the largest timbers of the St Pauls central nave roof

7.1 Methodology used to reconstruct the parent oaks

By noting the size and shape of timbers and the section of the tree they represent ('type of conversion') with details of the grain and outer sapwood present it is possible to reconstruct the size and type of tree ('parent tree') from which they were cut (Rackham 1972). By preparing this graphically and using a knowledge of the grain patterns and requirements of different conversion methods, ideally combined with information gained from tree ring studies, an even more accurate picture of the historic parent tree can be derived (Goodburn 1991, 1992). Here we recognise that large knots on the faces of boxed heart timbers, cut from whole logs, like those of the central nave roof trusses, represent branches in the parent trees existing when it was felled. We must also note that there are two closely related native oaks in Britain and they hybridize so we can only loosely talk of 'English oak'. All the original St Pauls nave central roof carpentry timbers had the clear, visually diagnostic, features typical of our native oaks such as boldly marked rays and cream coloured outer sapwood.

Particularly when dealing with very large historic timbers we can sometimes provide an outline picture of types of wooded land ('tree land') that no longer exist. It is likely that great oaks of the diameter, length and straightness needed for the very largest beams used in the eastern part of the nave roof probably do not exist in the areas where they were cut in the late 17th century, but this would require ground truithing. A detailed measured sketch was made of the west face of the tie beam of Truss 1 with the sapwood and large knots indicated and measured in (Fig 10 a). Using this information, graphically represented, an outline reconstruction of the great parent oak can be made allowing, a little height for felling and extra girth for the bark and sapwood largely removed (Fig 10 b). It appears that the Truss 1 tie beam parent tree was actually slightly smaller and a little less straight than some of the trees used for the other eastern tie beams, such as that in Truss 4 (Fig 2), though it was still huge. To appreciate just how large and tall this parent oak was, a typical, large managed woodland, or rather tall hedgerow standard oak, such as was used for more common place timber frame construction at the end of the 17th century, is shown alongside that derived from the Truss 1 tie beam. Not only where the parent trees for the largest tie beams of fairly large girth at, *c.* 0.65-0.75m diameter at breast height, but they were also unusually tall, straight and had little taper compared to typical English managed woodland oaks then and still found in ancient woodland today. The parent tree for the Truss 1 tie beam was still around 0.45m diameter at over 15m from the ground.

7.2 The type of tree land environment required for the parent trees for the great St Pauls tie beams to grow

The form of great parent oak reconstructed can now occasionally be found either in very old high forest plantations or clumps of large parkland trees where those near the middle of a planted clump tend to grow straight with few low branches. Up until *c.* 1250 AD remnant areas of natural, high, dark, and wildwood-type woodland have been shown to have existed in some parts of England. This type of tree land could produce, huge straight oaks sometimes even knot free for over 8m (Goodburn 1992, and 1998). These conditions produced narrow annual rings, straight grain and a slow taper in most trees. By the 17th century very little of this type of woodland still existed anywhere in western Europe but substantial areas still survived in what is now eastern Poland and southern Lithuania and the fine quality slow grown oak there was much exported. The same situation pertained in NE America in some areas and some oak similar to the English material was also exported from there. Only intensive tree-ring sampling could rule out the use of imported oak in the Wren period cathedral, although the sheer size and some of the documentary record, makes it plain is very unlikely for the largest structural elements. On balance we might suggest that the great, straight and tall oaks felled for the largest St Pauls roof timbers probably derived from clumps of large timber trees grown in some form of parkland setting. Such timber would have been much prized for naval use at this time and the St Pauls roof project was clearly lucky to obtain them.

7.3 Timber size comparisons

The eastern central nave roof truss tie beams appear to be the largest currently known oak timbers recorded in any historic English roof, demonstrating the prestige of the project. They are longer than, and of a similar scantling to, the 14th century Ely cathedral octagon timbers which previously held this position (Rackham 1976, 75). The largest St Pauls tie-beams were over 6ft longer than the earlier Ely timbers (Figs. 2, and 10 a). Bearing in mind the great length and comparative lack of taper of the longest tie beams it is really quite surprising that Wren did not chose to use a coniferous wood alternative for these timbers from either northern Europe or North America. These coniferous timbers were clearly coming into wider use at this time as MOLA recording work in timber framing of the 1690's at Middle Temple has shown (Goodburn and Minkin 1996 un pub). The diarist Samuel Pepys refers to the importation of huge straight American conifer logs 30 years before the work on the St Pauls main roofs (Pepys Dec 3, 1662.

7.4 The weight of great parent oaks used for the long tie beams of the eastern trusses and that of the freshly cut beams

Not only were the great timbers required for the St Pauls roof carpentry huge and some very long, but they were also very heavy. The logistical problems that were posed by having to move them without modern logging trucks and loading cranes were enormous. As the documentary records show this was a key issue for Wren and his master carpenters. Limited space here does not allow a full reconstruction of the issues involved in transporting and handling the largest timbers and jointed roof assemblies but we can cite some basic parameters for the very largest elements. The parent logs for the eastern, single piece tie beams would have weighed around 2.7 tonnes using a standard average weight for freshly cut 'green' oak of *c.* 1.073 tonnes per m3 (Millet and McGrail 1987, 106). This is heavier than water so freshly cut oak will not normally float in fresh water, or often even in salt water, so rafting the timber was not an option. We can be reasonably sure for practical reasons and some of the information in the surviving documentary sources cited above, that in fact the largest timbers would have been cut to their final dimensions near the felling site. If they were both hewn and sawn out as described below, they would have still weighed *c.* 1.4 to 1.5 tonnes taking a mid-length dimension of *c.* 370 by 280mm and length of 14.08. Some may have weighed a little more. This approximate figure happens to be close to the nominal oak timber volume/weight measure used in the timber trades until the 19th century of a 'load', usually given as 1.5 tons or *c.* 30 cubic ft. The difference in weight between the parent log and freshly cut beam shows why there was a great incentive to convert the larger timbers before long distance haulage. It also shows the volume of oak heartwood timber that would have been produced as left-overs which could have been sold for re sawing down for more domestic scale structures.

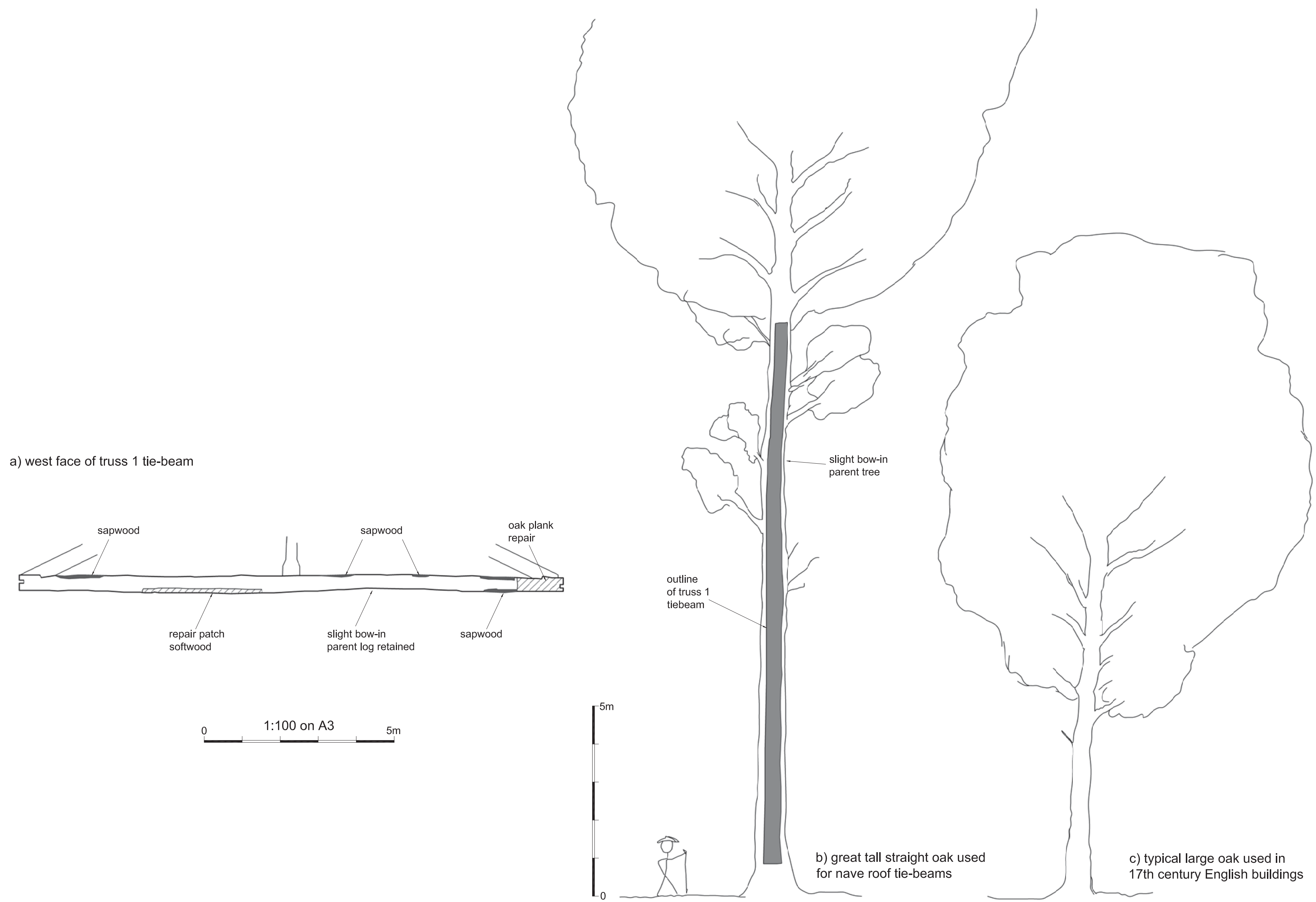

Fig 10 Diagram attempting to illustrate the size and form of the great oaks used in the eastern trusses with single piece tie beams, a) The western face of Truss 1 tie beam, showing its slightly curved shape, zones of sapwood and some more recent repair patches, b) The outline of the great oak (Parent tree) from which the beam was cut, c) The outline of a more typical large oak used in English buildings of the period.

8 Evidence for how the beams were cut out, the 'conversion' methods used and some wider inferences that can be drawn

8.1 Hewing the beams for the roof trusses near the felling site

It is clear from the building accounts that the modern practice of moving whole large oak logs was not carried out for the largest roof elements used in the nave roof. Wren specifies that what appear to be the great single piece tie beams were to be cut somewhere near the felling site to 'die square' beams 47 ft long as far as practicably possible. This would have saved much labour and cost as the large waste slabs of green oak could have been, either cut up for much smaller elements such as common purlins where they were thick enough, or sold off locally. In medieval times 'waste' timber, lop and top, and chips produced at the felling site were often sold locally to defray the cost of the laborious carriage of heavy large timbers. Slabs sawn off the sides of large oak timbers are often found used for low status secondary uses around 17th century shipyard sites in east London, though much material must have gone for fuel as it does from rural sawmills in England today. It may indeed be that the building accounts might note the resale of these materials, possibly indicating buildings near the felling site which might have been built with leftovers from the preparation of the unusually large St Pauls roof timbers?

Fig 11 Detailed photographs showing the south end of the Truss 9 tie beam with its sawn side axe hewn lower face

However, apart from sawing a much older technique of conversion also left traces on many of the longer St Pauls nave roof timbers, that of squaring up with axes or 'hewing'. This general method of timber conversion died out very early in England though it is even now in use in some remote parts of continental Europe. However, experimenters in historic woodworking and some timber frame carpenters have rediscovered the craft of hewing large oak beams in the last few years and so the quality of the workmanship evidenced in the St Pauls timbers can be more practically assessed (Photographs of such work in progress are also available, if required).

It is quite clear from the irregular scalloped surfaces of the smaller ends of many of the longer nave roof timbers that ‘hewing’ was the technique used to remove sapwood, bark and waste heartwood where the parent logs were only just big enough. Several meters of the smaller ends of many of the single piece eastern tie beams had moderately roughhewn faces with some sapwood left on the corners. A clear example of such axe hewn surfaces surviving on the south end of the tie beam of Truss 9 is shown in Figure 11. The hewing was only moderately regular not finished by smooth broad axe work, as it normally was in medieval London carpentry. Detailed recording of post-medieval carpentry work in southern England has shown that by the 17th century hewn surfaces were typically not expected to be very smoothly, broad axe finished but a moderately flat, regular surface was generally adequate (Goodburn 2009, and archive reports on 17th carpentry at Middle Temple, and St Ethelburgas church, Goodburn and Minkin 1996). No evidence for the shipwright’s practice of surface smoothing with an adze was found on any of the St Pauls timbers.

Fig 12 Detailed photographs showing of Truss 9 looking west, shows a ridge left where sawing out the face from both ends converged but did not quite meet, probably indicative of sawing on two high trestles. Also showing a combined joint and truss number cut with a 2" chisel and given a ‘tag’.

Also unpublished work by some of the new wave of English timber framers has shown that following marking out a log, firmly held in place, it was then scored at intervals with a heavy, felling-type axe. This was followed by using the same tool to split off large amounts of waste, close to the full depth of the scores (photos available if needed). The rather rough, uneven surface that generally then resulted was then chopped i.e. hewn back with axe blows at a shallower angle, using a plumb bob occasionally, to check the face being hewn was fairly plumb. These general hewing stages were the same as used in later medieval times, but usually this was where the carpenters hewing stopped by the 17th century. Often traces of the scoring grooves from the first cutting stage and facets from the next stage were left rough on hewn surfaces at this time as is shown in the hewn surfaces of the central nave roof timbers. On the soffit of the Truss 9 tie beam at the S end, and in several other examples, the remains of scores slightly over cut and very clear, rough, relatively narrow axe facets can be seen (Fig 11).

Even though God could see this workmanship, those who ultimately paid for it could not, and so a very smooth regular finish was obviously not deemed necessary by the master carpenters. So it seems that the extra time and money required for that final stage of creating a smooth hewn finish was not made available even for this nationally important prestige project. This contrasts both with late medieval practice and also greatly with the smooth, generally planed surfaces, found on the timbers in the more accessible parts of the cathedral such as the nave aisle roofs where the great and the good had access.

In most cases the hewn surfaces only survived at the smaller ends of the timbers with either all or *c.* 75% of the length of the beams having sawn finishes. So we see an economically minded combination of sawing and hewing used except for the largest and straightest of the logs they could obtain, where the faces were all sawn, such as in Truss 4 (Fig 2).

8.2 Sawing out the great oak timbers the predominant conversion method

Most of the surfaces of the roof timbers in the central nave roof still show clear manual sawing marks from accurately carried out ‘pit sawing’, the most common technique of sawn conversion used in London carpentry from the early 15th century (Goodburn and Minkin 2002). With pit-sawing the sawyers did their long wise cutting of minimally trimmed logs or axe hewn baulks, from one end of the timber to the other, leaving a small right angle triangle of split surface at one end. This distinctive signature of the pit-sawing technique is clear on several of the roof timbers examined, with a particularly clear example visible on the south end of the Truss 24 tie beam in western the portico section of the roof. Although we would expect pit-sawing to be the dominant technique used at the end of the 17th century evidence of another technique of sawing was also found on two tie beams of the eastern half of the nave roof. This was traces distinctive of sawing on two high trestles or possibly some form of raised gantry. The photograph (Figure 12) shows this evidence on the N end of the Truss 9 tie beam. With this method of sawing the sawing was carried out from both ends resulting in the cuts or ‘kerfs’ meeting on the sawn faces usually leaving a small un-sawn ridge where the last section split off. Experimental sawing shows that wedges driven into the saw kerfs to keep the timber from binding on the blade often cause the last section to split. As we already know from the surviving building accounts that the timbers were derived from at least two, if not several more sources, then the use of slightly different conversion methods for identical roof elements may indicate be a mark of separate origins. The widespread and distinctive use of thickened ends (rather like jowls on main post heads) in the rafters and king posts made special demands on the sawyers and or master carpenters marking out skills as two sawn surfaces for each face had to be accurately created, except where a spiked on thickening plank was used instead. Only in a few cases could over cut marks be seen reaching into the jawled end sections. It is likely that even where sawing was the predominant method used, at least two faces would have been roughly hewn first.

9 Surprising evidence for poor building site practice

9.1 The hoisting rope damage to most of the roof truss tie beams

During the first walk over survey strange multiple grooves were noted on the top corners of most of the tie beams of the roof trusses in the central nave roof and initially their function was uncertain. However, later it became obvious that they had been made by the frequent passage of ropes under load. The deepest were measured at *c.* 18-20mm wide and up to 30mm deep. On the top corners of the tie beam for Truss 1 over 20 such rope wear grooves were found. The tie beams had clearly been used as purchase points to hall up materials, in small parcels, for the brick layers and masons creating the vaulting for the nave ceiling. This, largely brick, vaulting now also acts as the floor of the roof space so it is easy for us to forget that it had to be built from temporary staging once the side walls, and clearly also the roof trusses, had been erected. With the roof up, even if not permanently covered, the masons and bricklayers could have worked undercover allowing the slow setting lime mortar to go off without being damaged by weather. The relatively low clearance between the top of the vaulting and the bottom of the roof trusses would have made it difficult to rig pulley blocks with hooks below the beams and it may also have been slow work to move the purchase point as the brick lying progressed during the day. Hundreds of tonnes of mortar, and bricks would appear to have been lifted up into the roof space by these crude means. No doubt the bricklayers labourers thoroughly earned their wages and many ropes were worn out in the process!

Fig 13 Photograph showing details of the simple through splayed scarf and original inset iron reinforcing strap, in the soffit of the tie beam of Truss 20. Shows how recessing of the dovetail ended iron strap was crudely done with a slack fit and cutting away of the ends of the scarf joint. The paint is modern

9.2 Evidence of a lack of consideration for the overall standard of finish of the work where it was little seen

The bricklayers and masons obviously did not respect the laborious work of the carpenters and sawyers and thought little of marring the appearance of the carpenters work. Clearly the loads hoisted up were relatively small, probably including baskets of bricks and buckets of mortar, as they clearly did not use a fixed windlass or capstan such as were fitted elsewhere in the cathedral (Hewett 1985, 196, Clearly these machines would be very worthy of recording).

10 Partially blocked mortises in tie beam undersides or soffits, as evidence of the temporary support of the roof framing

During the examination of the roof trusses spanning the high western dome, Trusses 15, 16, 17 and 18, traces of mysterious empty mortises and staining were found at their extreme north and south ends on the soffits (Fig 3). These empty mortises were partially blocked by the piers and pads located under their ends which were clearly original historic workmanship. Initially, it was suggested that these mortises were evidence for the reuse of these timbers but in a short while it became clear from their regular positioning and traces of joint lay out scribing, that they must instead have been evidence for the use of temporary raking posts under the tie beams (Fig 14). These posts would have sprung from completed masonry walling lower down and acted as temporary supports for the roof trusses before the side walls of the roof space were eventually built up. At this point the side aisles had been constructed (J Schofield pers. com.)

The key conclusion here is that the carpenters were well ahead of the work of the masons and brick layers and there were actually good practical reasons for this. The raised roof would protect the brick vaulting during their construction allowing time for the slow setting lime mortar to harden. It may also have allowed the bricklayers to work longer hours in the winter and during bad weather. But here light may have been a problem, although much less so for finishing the domes if the sides of the roof were still partially open until that work had been done with the roof side walls and piers under the tie beam ends, then completed as the archaeological evidence indicates was the case. The multiple deep rope wear marks also indicates that the suggested stages of work must have been the case as there would have been no need to hoist anything up if the upper face of the vaulted ceilings had been completed.

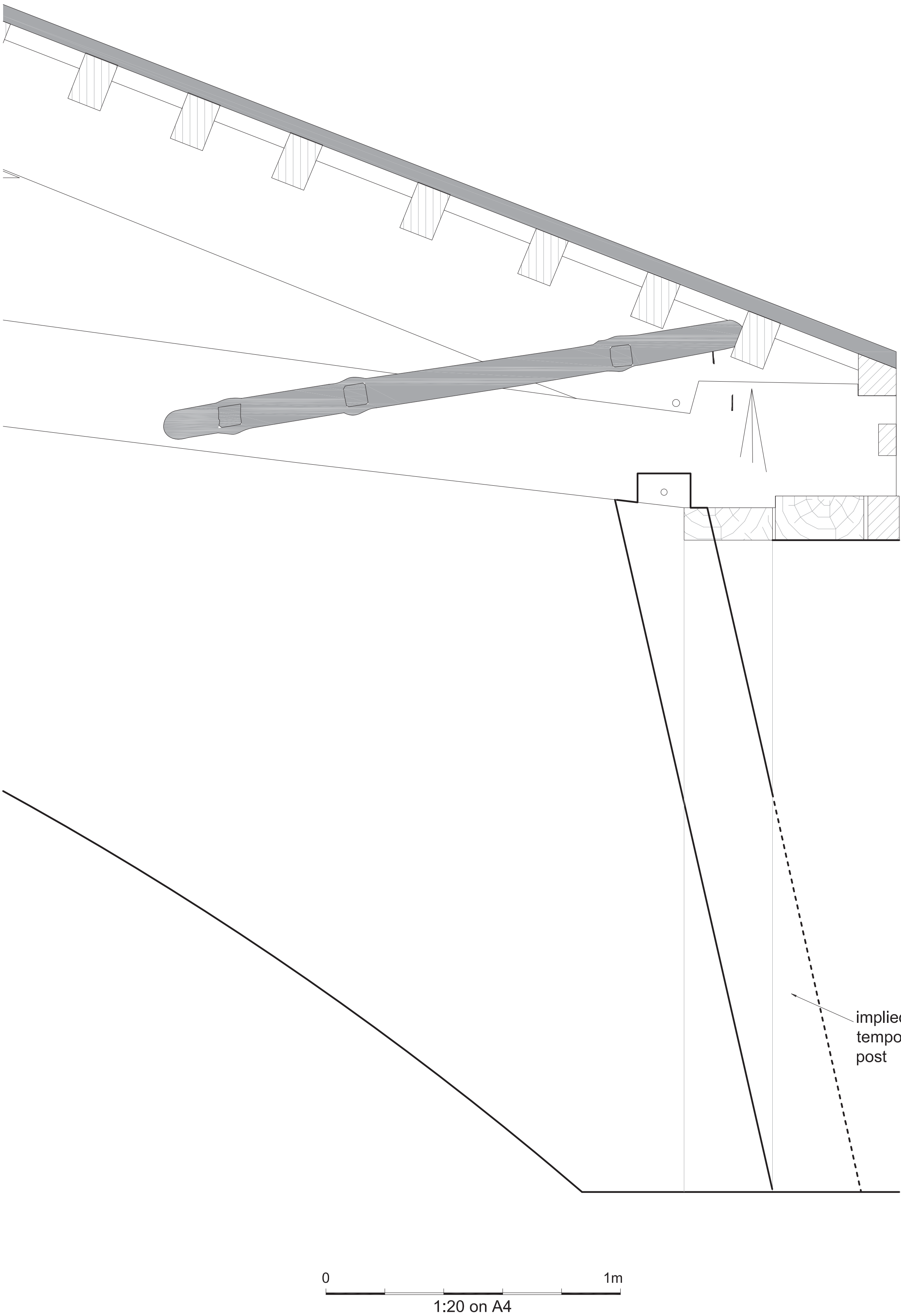

Fig 14 Diagram showing an interpretation of the probable original function of the partially blocked mortices on the undersides of the tie beam ends over the large western dome in St Pauls cathedral nave roof. The indicated, probably raked, post would have provided temporary support for the roof at this point until the work of the masons and brick layers could replace it.

11 A compass scribed daisy wheel, tentative traces of late 17th to early 18th century superstition and beneficial magic?

During the final stages of the one day long investigation of the St Pauls central nave roof it was possible to rapidly examine some of the roof carpentry of the extreme western part of the roof where it extends over the portico. This work was particularly hurried and the lighting poor, but the existence of a pair of relatively recent, rather crudely made, ½ trusses was established (Trusses 22a and b Fig 1). The tool mark evidence and patina of some of the oak timber found in these additions, such as circular saw marks, isolated the most recent timbers (The work is thought to possibly date as late as 1903, J Scofield, Pers. com.). However, some of the oak timbers had relict joints, traces of pit sawn conversion and a patina just like that of the, in-situ historic roof timbers of the nave central roof. One on the north side (Truss 22b) had simple lap joints and proportions similar to those of the rafters in the central nave roof trusses. It would appear to have been originally a rafter from a common rafter roof in another area of roofing at St Pauls. A very brief application of low angle torch light revealed a faintly scribed 'daisy wheel' mark (Fig. 15) on this timber, which although cutting through the pit saw marks, appeared to be ancient i.e. dating to the *c.* 1690's to early 1700's. These marks were made with compasses, which were used first to scribe a circle and were then set to the radius of the circle and used to scribe a series of petal-like arcs within it. The daisy wheel marks are often found on historic building timbers and there are two schools of thought as to their meaning and use. One school suggests that they were marks designed to guard against bad hexes from witches (Hence they are sometimes called 'witch marks' Easton 1998). The alternative view sees them as geometrical design aids used to develop accurate angles and shapes by carpenters and masons (Smith 1997). The first named writer has seen much variation in the execution of these marks and their location and would suggest that both explanations could apply, depending on the location and execution of the marks. In the case of the daisy wheel on the reused rafter type timber from in Truss 22 b, it's very faint execution might possibly indicate that it was trial work by an apprentice trying to learn the skill of accurate scribing with a compass, on hard oak timbers.

Fig 15 close up of a large historic oak rafter of St Pauls cathedral type reused in recent additional truss 22b over the portico roof. The faint outline of part of a compass drawn daisy wheel, possibly a 'witch mark' is visible cutting through the pit saw marks

12 Conclusions, key products of this limited and closely targeted investigation of the roof carpentry of the great timber framed central nave roof of St Pauls cathedral

It is hoped that this report has been able to summarise, in some detail, the key new information gained during the recording work and subsequent analysis carried out by the small MOLA team, with J Schofield, in the central nave roof of St Paul's cathedral.

It is also hoped that the report goes some way to setting some of the main findings in a wider context, although further checking of and integration with, the historical sources is clearly required for the purposes of the wider investigations of the Wren period cathedral.

Carpentry practice at the end of the 17th century and start of the 18th was undergoing great change when aspects of medieval practice were gradually being rationalised and modified with the widespread use of new materials such as wrought iron strapping and bolts. The St Pauls roof carpentry evidence sheds light on these changes and some aspects of continuation of earlier practices such as an almost religious adherence to the use of oak for high status buildings even under a very weather-tight lead covered roof where long, regular imported softwood timber would have been more suitable, small timbers were lighter more easily worked and cheaper.

Even though quite limited this investigation and recording work has also made it possible to visualize, in more tangible detail, how the building of a cathedral on this scale involved the resources of the whole of England with many of the huge oak timbers being cut at a great distance from London. St Pauls was not just built in London, but some of the carpentry work (and indeed masons work) began hundreds of miles away. The eastern part of the central nave roof has also been shown to contain the longest, large oak building timbers, currently recorded in any English historic building flagging up the national pre-eminence of the project at the time, despite periodic funding crises known from the documents.

Although much of the initial work, such as the sawing of the timbers and joint cutting, was carried out to a high standard some other aspects of the work were less carefully executed, such as the crude scarfing and fastening of the horizontal tie beams in the wider western trusses. Evidence of aspects of building site practice that resulted in minor damage to the carpentry of the roof through wear by hauling ropes used by the bricklayers is also described. Perhaps these strands of evidence indicate less close supervision on-site by Wren and his team or reflect the fact that towards the ends of the project he must have been much less able to examine the work carried out at height. Evidence was also recovered for step wise phases in the building of the roof in the form of partially blocked, temporarily used, mortise joints showing that in the area of the western dome the work of the carpenters was well ahead of the bricklayers and masons.

Finally, this limited archaeological study of the carpentry of just one of the great timber framed roofs of St Paul's cathedral has shown that it is possible to link different sections of work on the fabric of the building to different, historically known, master carpenters i.e. Longland and Jennings. This is very rarely the case in detail and it is likely that this could also be carried out through the forensic archaeological investigation of other areas of the historic carpentry at surviving at St Pauls.

12.1 Some tentative suggestions for possible further archaeological recording of the historic carpentry of St Pauls cathedral

It is hoped that this limited archaeological investigation and targeted analysis of historic carpentry in St Pauls cathedral has demonstrated the potential to gain much information about the fabric of the great building, and the hows', and whos' of what went into realising Wren's iconic design. Other further studies likely to yield new information include a systematic tree ring analysis by discrete coring linked to recent and possibly future recording work. If the state and character of the timber in the roofs of St Pauls and related structures such as the windlass and capstan, stairs and partitions etc. are similar to that found in the central nave roof then tree ring studies have considerable potential. In some cases precise felling dates for some timbers could probably be obtained but given close historical dating, the investigation of the origins of the timbers and their growth rates and age would be the most historically and archaeologically important results.

13 Bibliography

Easton, T, 1998 Ritual Marks on Historic Timber, *The Mortice and Tenon*, 7-9

Goodburn, D, 1991 b *Wet sites as archives of ancient landscapes*, in eds. J Coles and D Goodburn, *Wet Site Excavation and Survey*, 51-53

Goodburn, D, 1992 Woods and woodland: carpenters and carpentry, in C, *Milne Timber Building Techniques in London 900-1400*, 106-131

Goodburn, D, 1998 The death of the wildwood and birth of woodmanship in SE England, In C, Bernick ed. *Hidden Dimensions*, University of British Columbia Press, 130-138

Goodburn, D, 1998 un pub MoLAS archive analysis report- *New Lights on Aspects of the Roman Woodwork at the Regis House*, Site Code KWS94

Goodburn, D, 1999 Timber Studies, in J, Hill and A, Woodger, Excavations at 72- 75 Cheapside/ 83-93 Queen Street City of London, *MoLAS Archaeological Study Series 2*, 47-52

Goodburn, D, 2001 The woodwork in, The excavation of an Elizabethan/Stuart waterfront siteon the north bank of the river Thames at Victoria Wharf, Narrow St, Limehouse, London E14, *Post-Medieval Archaeology:35*, 53-95

Goodburn, D, 2009 Woodwork from Southwark, in *Great Houses Blatherwick*, S, and Bluer, R, 2009 *Great houses, moats and mills on the south bank of the Thames; Medieval and Tudor Southwark and Rotherhithe*, MoLAS Monograph Series 47, 200-221

Goodburn, D, and Minkin, J, 1996 a, Un Pub MOLAS draft Archive Report, *Woodworking evidence recorded at 1-4 Middle Temple Lane, city of London*, Site Code MTE96

Goodburn, D, and Minkin, J, 1996 b, Un Pub MOLAS draft Archive Report, *St Ethelburga The Virgin Bishopsgate, EC2, City of London*, Report on the third phase of the work on the salvaged Woodwork, Site Code SEH94

Goodburn, D, and Minkin, J, 2002 Timber Studies In J. Ayre and R, Wroe-Brown, *The London Millennium Bridge; Excavation of the medieval and later waterfronts at Peter's Hill, City of London and Bankside, Southwark*, MoLAS Archaeology Study Series 6

Harris, R, 1979 *Discovering timber framed buildings*, Shire Guide. Aylesbury

Harris, R, 1989 The Grammar of Carpentry, *Vernacular Architecture* 20, 1-8

Heard, K, and Goodburn, D, 2000 *Investigating the Maritime History of Rotherhithe*, MOLAS Archaeology Study Series 11

Hewett, C, 1980 *English Historic Carpentry*

Hewett, C, 1985 *English Cathedral and Monastic Carpentry*

Millet, M, and McGrail, S, 1987 *The archaeology of the Hasholme logboat*, Archaeological Jnl. 144: 69-155

Milne, G, and Milne, C, 1982 *Medieval waterfront development at Trig Lane*, LAMAS, Special Paper 5

Milne, G, 1992 *Timber Building Techniques in London c. 900- 1400*, LAMAS, Special Paper 15

Miles, D, and Russell, H, 1995 Plumb and level marks, *Vernacular Architecture*, 26, 33-38

Millett, M, and McGrail, S, 1987 *The Archaeology of the Hasholme Logboat*, Archaeology Jnl 144, 69-155

Rackham, O, 1972 Grundle House: On the quantities of timber in certain east Anglian buildings in relation to local supplies, *Vernacular Achitecture* 3, 3-8

Rackham, O, 1976 *Trees and woodland in the British landscape*

Saunders, A, 2001 *St Paul's the story of the Cathedral*

Schofield, J, 2011 *St Pauls Cathedral before Wren*, EH

Smith, L, 1997 Compass, Cut Circle and Daisy Wheel, *The Mortice and Tenon*, 5, 3-5

Yeomans, D, 1989 Structural Carpentry in London Building, In H Hobhouse and A Saunders, *Good and Proper Materials; the Fabric of London since the Great Fire*, Royal Commission