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The Engineering of Stonehenge

JULIAN RICHARDS & MARK WHITBY

Introduction

Julian Richards

The experiments

THE EXPERIMENTS DESCRIBED IN THIS PAPER, and the thoughts which both preceded and arose from them, are the direct result of the involvement of both authors in the production of a BBC programme in 1994. The series, 'Secrets of Lost Empires', examined the greatest and most enduring engineering challenges of the ancient world, among which is the construction of Stonehenge, or more precisely, of the sarsen horseshoe and circle which form the most impressive elements of the stone structures. Within these, the single largest element is the Great Trilithon, now ruinous, but the largest of the individual stone settings, each of which consist of two uprights and one horizontal lintel (Fig. 1). The brief was to demonstrate, using human effort and such technology as could reasonably be expected to have been available to the builders of Stonehenge during the earlier part of phase 3, now dated to between 2550 and 1600 BC (Cleal *et al.* 1995, 167) how this could have been accomplished. The nature of the experiment was dictated by the evidence provided by Stonehenge itself, the sarsen stones, estimated as weighing up to 40 tonnes, for which no convincing evidence for local origin could be produced. A possible source on the Marlborough Downs, some 30 km to the north, was first suggested by Samuel Pepys in 1665 (quoted in Brentnall 1946) and was reaffirmed by Colt Hoare in the early nineteenth century (Colt Hoare 1812, 149–50). After considerable subsequent debate this source appears to be confirmed (Pitts 1982, 119–23; Green, this volume). At Stonehenge pairs of the largest of these stones have been dressed to a more regular shape, jointed in a manner reminiscent of carpentry techniques, raised to a vertical position and capped with lintels of similar stone weighing up to 10 tonnes. The experiment could consequently be seen to consist of three individual tasks. The first was to move an upright,

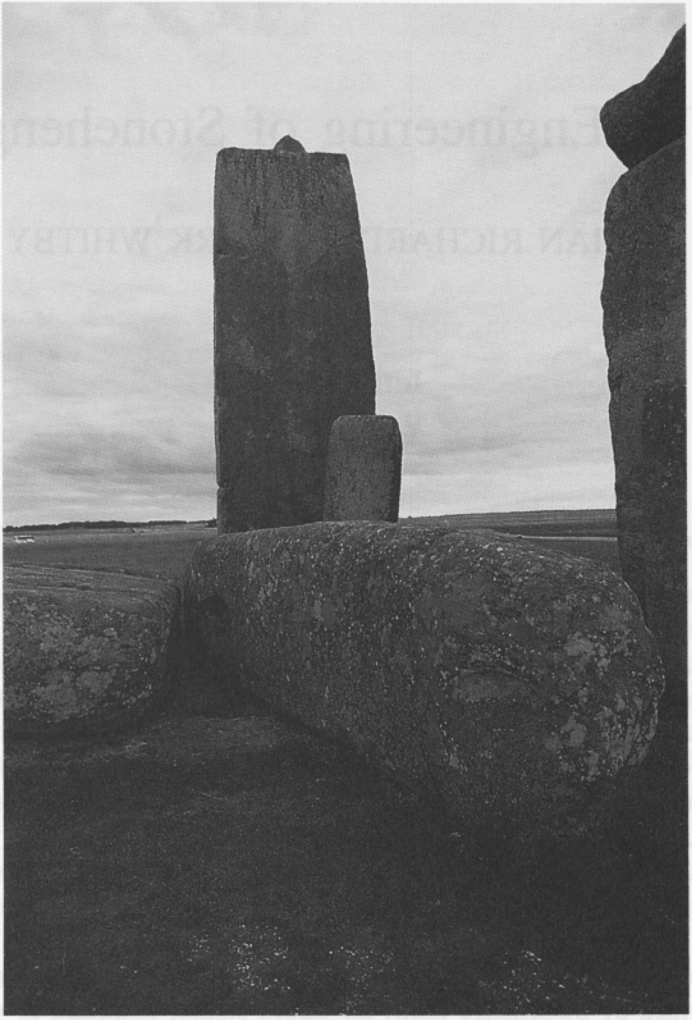


Figure 1. The ruins of the great trilithon. The fallen lintel lies in front of stone 56 with its pronounced tenon. (Copyright: Wessex Archaeology. Photograph: Elaine Wakefield.)

the heaviest of the constituent stones, both on flat ground and up a slope of approximately 1 in 20, the minimum slope estimated as being necessary for human transport from its assumed source to Stonehenge. The second task was to raise the upright to a vertical position, and the third, after placing the second upright in position using modern methods, was to lift the lintel into place.

The brief was not presented to archaeologists but to an engineer (Whitby) who was asked to devise possible methods for accomplishing the specified tasks with an archaeologist (Richards) to provide details of available technology and the archaeological evidence for construction methods.

Previous experiments and the development of a visual orthodoxy for the construction of Stonehenge

During this century there has been no shortage of opinion about the means of stone transportation or erection and the consequent labour requirements. Of early authors Stone (1924a and b) offers over-confident solutions accompanied by scale models while, in a flurry of activity in the late 1970's both Garfitt (1979 and 1980) and Hogg (1981) solve the problem diagrammatically. Estimates of labour requirements have shown considerable variation, for example the task of moving stones has been suggested as requiring between 90 individuals for 30 tonnes (Garfitt 1979) to 600 for the steepest parts of the route and the heaviest stones (Startin and Bradley 1981). Atkinson (1956, 115) increases this requirement to 1100 men, rising to 1500 for the steepest parts of the route. Such a wide range seems inconsistent when the motive potential of one person appears to have been estimated at a relatively consistent level. Factors which influence the estimates include perceptions of the vehicle to be utilised, while those produced by some of the earlier authors may have been based on preconceptions that the prehistoric workers were short in stature and therefore provided less motive power than their modern counterparts.

Practical experiments have also been carried out, ranging in scale from the transport of a replica bluestone by Atkinson in 1954 (Atkinson 1956, 107–10) to the considerably more ambitious work carried out in 1991 by Pavel (Pavel 1992). While such experiments clearly have a value in establishing some basic principles of transportation and engineering, they were not carried out with replica stones approaching the full size and weight of the largest sarsens and direct extrapolation from their results is consequently unwise. These experiments should also be viewed in the context of the many and varied methods of moving large stones practised around the world (Smith 1866).

Small-scale experiments, theoretical engineering and imagination have combined to produce a standard orthodoxy for the building of Stonehenge. This is best rendered in graphic form in the reconstruction painting until recently displayed at Stonehenge and which appears in the current site guide book (English Heritage 1995, 26–7). In this reconstruction, stones are transported on sledges running on rollers, are raised from the horizontal by means of what appear to be ropes, sheerlegs and timber props and, finally, lintels are elevated using levers on a crib of interlaced and apparently squared timber. What was offered by the BBC was the opportunity to test these and alternative approaches using full-sized replica components of the largest element of the sarsen horseshoe, the Great Trilithon.

Archaeological evidence and assumptions

The dimensions of the surviving intact upright (stone 56) of the Great Trilithon were used to produce two matching reinforced concrete 'stones'. The fallen lintel (stone 156) was similarly replicated. Although mortice holes and tenons were cast into the 'stones', no attempt was made to replicate the original asymmetry of the two uprights (they were clearly of unequal length) or any minor irregularities in their overall shape. Tests suggested that the density of the concrete, calculated as 2380 kg/m^3, was very similar to that of sarsen. The weight of each upright was calculated at approximately 40 tonnes and that of the lintel at 10 tonnes.

The profile of the hole for stone 56 has been known since its investigation in 1901 (Gowland 1902) and this profile was used as a directly applicable guide to depth and shape. The recently published results of subsequent investigations (Cleal *et al.* 1995), while providing additional detail for stone 56's hole (op. cit., figs 149–50) suggest that there is little consistency in stone-hole morphology. Beyond the evidence from subsoil features, Stonehenge itself appears to offer few direct clues to the methods involved in stone erection. Antler picks provide an obvious indication of the methods used for hole digging and the evidence for their curation suggests an importance beyond mere functional considerations. The direction of ramping demonstrated by excavated stone-holes suggests whether stones were erected from the 'inside' of the structure or from without. In addition, in the absence of a fully understood internal sequence of construction within phase 3, common sense suggests that within phase 3ii (sarsen circle and trilithons) the horseshoe of sarsen trilithons must have been built before the outer sarsen circle was completed.

Certain assumptions were made concerning the materials and technology available at the time of Stonehenge's construction. Inevitably much evidence is provided by areas with good organic preservation. The ability to fell substantial mature trees and to split and work their timber is well documented from the Earlier Neolithic onwards (Coles *et al.* 1978). Stone tools were readily available for both felling and shaping and are capable of efficiently working green oak. Experiment has shown that longitudinal splitting of substantial straight-grained oak trunks can be successfully achieved using seasoned wooden wedges (J. Keen, pers. comm.). The environmental evidence for the early second millennium BC from the immediate environs of Stonehenge suggests a landscape largely devoid of trees. Woodland, largely managed, may have been restricted to small pockets or to the steeper margins of the adjacent river valleys (Allen in Cleal *et al.* 1995, 168–9) although the evidence from Coneybury Henge (Richards 1990, 154–8) suggests woodland regeneration at this period. In contrast to the sparsely wooded environs of Stonehenge and the similar conditions which can be suggested in the Avebury area (Smith 1984, 117–18) the suggested route of the stones from the Marlborough Downs would provide a far wider resource zone within which quantities of timber from both semi 'wildwood' and from more managed woodland would have been available.

The methodology developed for the experiment depended not only on the use of timber but also on the use of rope. Although evidence for rope, or even for string, is rare within the archaeological record, the Wilsford Shaft, approximately 1.5 km south-west of Stonehenge, provided a remarkable survival. The waterlogged basal deposits of a Middle Bronze Age shaft or well contained fragments of a three-strand cord originally of 7 mm diameter and carefully made from an unidentified bast fibre (Ashbee, Bell and Proudfoot 1989, 62–5). Although this cord has been suggested as having a breaking load in the region of 250 kg, the planned experiments clearly required a more substantial rope (rope is greater than 1 in., 25 cm in diameter). An experimental length of rope made from the bast of coppiced Small Leaved Lime (*Tilia Cordata*) was made by Jake Keen of the Cranborne Ancient Technology Centre. The bark was retted and the fibres were then plaited into strands, three of which were themselves plaited together to make a comparatively simple rope. The length of the component bast fibres (over 4 m) and their strength, combined to produce a rope which only broke at its weakest point, where looped, at a breaking strain of 980 kg. Although, for health and safety reasons, modern but traditionally made hemp ropes were used for the construction tasks, this experiment demonstrated the practicality of producing ropes capable of withstanding the forces required.

Engineering solutions

Mark Whitby and Julian Richards

Moving the stones

The approach to moving large stones is inevitably dictated by their size, and solutions require modification as size increases. Atkinson (1956, 109–10) demonstrated that a small stone (weighing approximately 1.5 tonnes) could be dragged using a simple sledge across level smooth grass using a team of 32 haulers. Above this size it is possible that stones of up to 4 tonnes in weight could be carried by teams of up to 100 people grouped around a litter. Beyond this weight, however, the need to develop an economy of effort would seem to dictate that a more efficient system be developed.

Such systems will depend on how many stones are to be transported and how far, the nature of the terrain to be crossed and the maximum available labour force. It is quite feasible that a system which predominantly used brute force could be used when moving a heavy stone over a short distance. But the moving of 40 tonne stones over a distance of 30 km would surely have provoked serious consideration of a means that economised on labour, made the best use of the community and exploited the resources and skills available.

In the case of the Stonehenge sarsens, the terrain over which they were moved varies from the firm undulating chalk of the Marlborough Downs and Salisbury Plain to the level, but potentially wetter Vale of Pewsey. There are several suggestions for the precise route of the stones, the most enduring published by Atkinson (1956, fig. 4) and still broadly accepted 40 years later (English Heritage 1995, 16). Whatever the precise route, the varied nature of the terrain, with undulating topography and potentially wet areas, helps to dictate the approach to the development of a method of transportation. In this development a number of ideas were considered including the use of rollers, forming a timber cylinder around the stone and rolling it, 'crabbing' the stone along using levers and the use of ice as a medium across which the stone could be slid.

The orthodox method using rollers to move the stones was considered but rejected. Subsequent experiments in moving the 10 tonne lintel proved that it is a practical system, but has limitations. The direction of the stone is difficult to control on all but the most level ground and the method involves high risk as rollers have to be placed ahead of the moving object. As the load goes up, the system becomes prone to binding as the weight of the whole load will at times bear on only one or two of the rollers due to unevenness either in the rollers or in the ground surface. The latter can be overcome by running the rollers on a flat, possibly timber track, and the former by selecting rollers of a uniform diameter. However, directional control remains an issue, as any roller placed out of true to the track will cause the load to veer off.

Having rejected the use of rollers, consideration was given to sliding the stone. Ice is recorded as a suitably slippery surface employed in China but the climate of Late Neolithic Britain, combined with the porosity of the chalk across which the majority of the route passes, would render it an inconsistent and infrequently available surface. Other substances were considered; mud for which there is evidence of use in Egypt, powdered chalk, clay, mixtures of these and tallow. The latter, produced from animal fat, has been used until relatively recently to lubricate slipways for the launching of ships and was consequently thought to be the most suitable.

A system was devised, extrapolating from the technology employed in ship launching, that utilised an oak sledge on which the 40 tonne stone was lashed. The sledge consisted of a single slab of oak approximately 5 m long, 1 m wide and 300 mm deep, with a chamfered leading edge. A rectangular section keel was attached to the underside of the sledge (Fig. 2). The overall unladen weight of the sledge was estimated at 1 tonne. The sledge was set on a slipway, consisting of pairs of approximately 200 mm square section timber rails. These were set 750 mm apart and laid end to end to create a route, along which the stone on its sledge could be hauled. With the slipway timbers set into the ground, a firm base was provided, as well as side restraint that would hold the timbers, and hence the whole system, in position. For the purposes of this experiment the topsoil was removed and the rails laid on solid chalk. Examination of the chalk surface after five passes of the loaded sledge and the removal of the rails revealed no trace of surface compaction. The route of such a trackway would appear to be archaeologically invisible. The keel in the bottom of the sledge, running in between the inside faces of the timber rails, was intended to ensure that the sledge and its load remained on the slipway.

Investigations were made into lubricants for the slipway, with serious consideration being given to both 'mud' and tallow, but ultimately a proprietary Shell grease was

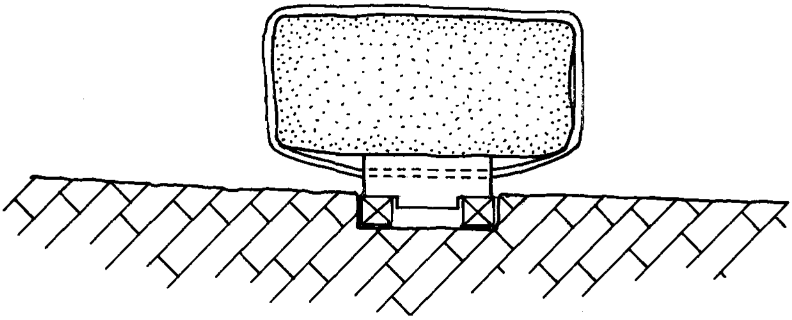


Figure 2. Cross section of sledge, rails and stone.

selected. This was readily available, is used on modern slipways, and has properties similar to tallow, but with a slightly lower coefficient of friction. Small-scale tests were carried out to check the feasibility of such a system, as the process requires a large bearing area between sledge and rails in order that the grease is not displaced by the pressure of the sledge.

Estimates of the coefficient of friction for the grease were 0.05, meaning that on level ground, a 40 tonne stone and sledge would require just over 2 tonnes of pulling force to move it. To pull it up the 1 in 20 slope dictated by the experiment would require an additional 2 tonne pulling force, increasing the total to 4 tonnes.

Conversely, to run the stone down a 1 in 20 slope should, in theory, require no effort at all. In both cases, however, an initial force would be required to set the stone in motion and break the sticking effect that came from the grease being forced out under the static weight of the resting stone. For the uphill pull it was estimated that this would momentarily increase the force required to 6 tonnes.

The use of draught animals, specifically oxen, to provide motive power was considered. Received wisdom was that oxen were difficult to work with and were unco-operative in teams unless trained together. Their use was therefore beyond the limits of this experiment but the possibility should not be ignored.

Estimates for the (human) labour requirements were based on the assumption that an individual can pull with a maximum force equivalent to their own weight. For the purposes of calculation an average weight of 60 kg was assumed but the actual average was estimated as being closer to 75 kg (approximately 12 stone). Experiments using a dynamometer with teams of eight confirmed this but suggested that allowances had to be made for increased inefficiency as teams grew larger. Reducing their combined efficiency to 50% it was estimated that a team of 200 individuals would be required. This figure would obviously be reduced by using heavier individuals or by increasing co-ordination of effort.

Although 200 individuals were estimated to be required and this number volunteered, only 130 were eventually available for the experiment. The volunteer group was of mixed sexes, ages and physical strength and can perhaps be suggested as providing a cross section of modern, if not prehistoric, society. For the purpose of moving the stone the group was divided into four teams, each strictly disciplined and co-ordinated by a single supervisor. Movement down the 1 in 20 slipway was initiated and maintained using 60 people (Fig. 3). This movement required a constant but lighter effort to maintain motion, indicating a frictional force slightly greater than the 0.05 that was estimated. However, returning the stone uphill required an extraordinary effort from all the volunteers assisted by the engineering staff.

Initially the stone was impossible to move, due to the combined friction load and the sticking force. To break the latter, the stone was rocked by two teams of four people using levers on either side of the leading edge, while the rest of the team maintained the tension on the ropes. Once freed the stone could be hauled at a slow walking pace up the 30 m long slipway by all 130 available volunteers. During the one-day period of the transportation experiment, the stone was hauled in total 150 m, twice uphill and three times down. Clearly the main limitation to this method is the length of slipway prepared and available but, if sufficient were laid, it was considered that it would have been feasible to move up a steady 1 in 20 slope for a distance in excess of 1 km in a day. On level ground or downhill a distance of 10 km a day could be achieved.

During the experiment approximately 50 kg of grease was used, with fresh applica-

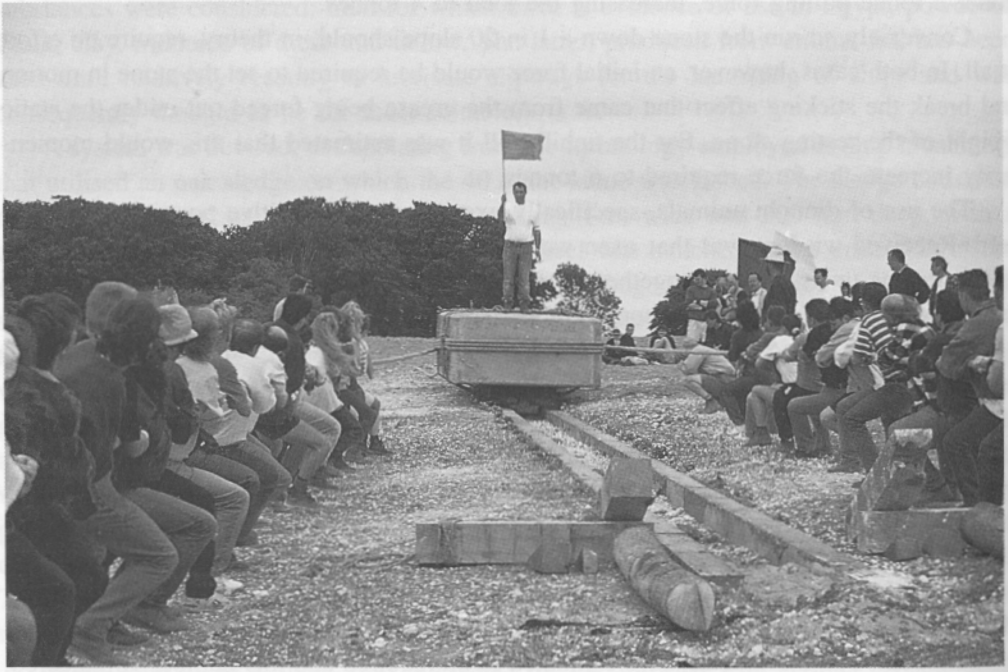


Figure 3. The upright pulled downhill. (Copyright: BBC.)

tions on the track for each pull. Were tallow to have been used, with its higher coefficient of friction (approximately 0.1), it is estimated an additional 70 people would have been required, making a total of 200.

Raising the uprights

This part of the experiment involved raising one of the 40 tonne uprights to vertical in a stone-hole (prepared by machine excavation) the profile of which was based on that of stone 56 excavated by Gowland. The assumption was made that the stone was inserted from the ramped side of the hole.

Most published diagrams and illustrations of raising the stones to vertical show various systems whereby the stone is levered up from its top end, or hauled up using ropes on a timber 'A' frame (see for example Atkinson 1956, 128; English Heritage 1995, 26–7). Both systems would require a lifting force of at least 20 tonnes, some 3.5 times greater than the maximum 6 tonne force generated by the team of 130 volunteers. Whilst the 'A' frame could give some considerable mechanical advantage and levers could be used to generate lifting force, both systems lack the necessary control that would ensure that the stone could be inserted into the hole without sliding forward on tilting and jamming against its front face. Precise positioning of the stone would be of critical importance as its recovery from a partially inserted position would have been extremely difficult. A system was required which allowed the stone to rotate to an angle of 70 degrees from the horizontal, to clear the front face of the stone-hole and finally to drop the remaining short distance into the bottom of the hole (Fig. 4).

The approach that was adopted recognised that for the stone to rotate successfully into the hole, it would require a hard 'pivot point' on which to rotate. An alternative means of generating the force required to rotate the stone was also sought. The most suitable pivot point that could be envisaged was one of stone and initial thoughts were that the upright could be notched in order to hook over the pivot stone as it rotated. The present appearance of the upright sarsens at Stonehenge does not support this concept which was eventually modified to one where the front of a wooden sledge, to which the upright was tightly lashed, provided the 'notch'. The pivot 'stone', triangular in section and reminiscent of some of the wedge-shaped stones in the sarsen circle, was made of reinforced concrete and was set immediately adjacent to the stone-hole, the line of the sloping face of which extended up through the sloping side of the pivot stone (70 degrees from the horizontal). A ramp of crushed stone (representing a chalk ramp) laid to a slope of 1 in 20 was constructed behind the pivot stone, and timber rails, identical to those employed in the moving experiment, were laid on its surface.

Trial models suggested that the pivot was best set 1500 mm above the ground level, so that the stone, bearing in mind it was heavier at its 'bottom' end due to its shape, was not in danger of overbalancing either forward when near to the horizontal or backwards once tipped to an angle of 70 degrees. The stone was placed on a sledge (smaller but of

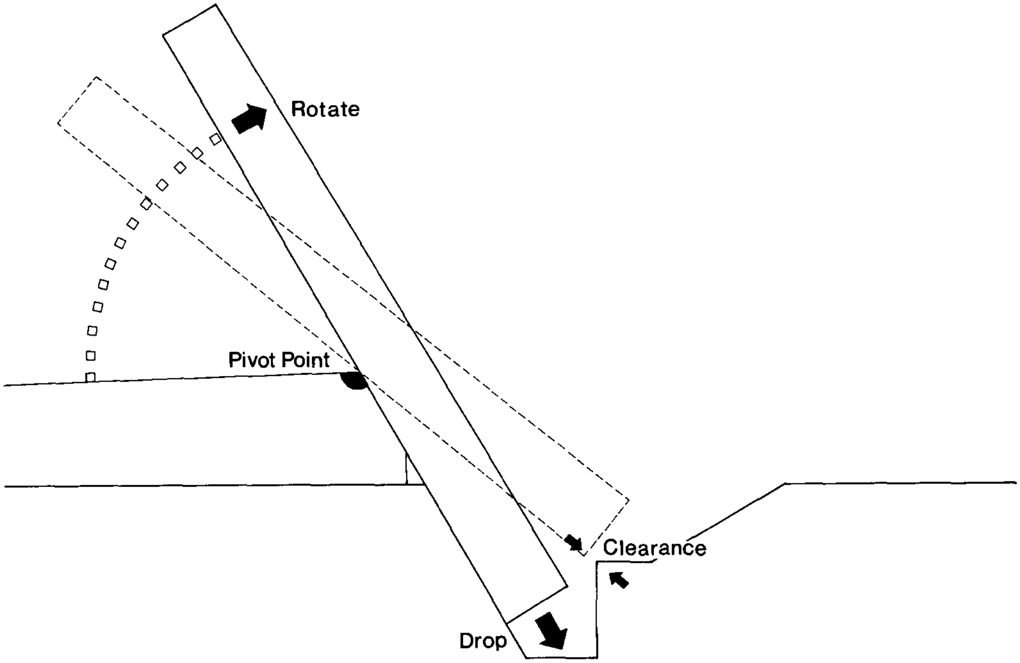


Figure 4.

similar principle to that used in the stone-moving experiment) on the ramp with its centre of gravity positioned to the rear of the pivot point. In order to provide force to assist with the rotation of the stone, timber rails were placed along its length and on these was placed a small wooden sledge to which were lashed six, 1 tonne concrete blocks. The principle of this method was that the near horizontal stone could be pivoted using the weight of the 'tilting stones' (Fig. 5) as they reached the tip of the stone overhanging the hole. A weight of six tonnes was calculated to be required for a pivot point set 1500 mm above the ground surface. The stone was lashed to the sledge in such a position that theoretically, on completion of its rotation through 70 degrees, the leading edge of the sledge would engage with the lip of the pivot stone. The stone would then be held momentarily in this position before breaking free of its lashings and dropping into the base of the hole. Once positioned, the sledge containing the tilting stones was gently pulled along its slipway by a small team of less than 50 people, with brake ropes attached in order to ensure that it could not be rapidly pulled off the edge of the stone. As the bundle of tilting stones reached the bottom of the 40 tonne stone, their weight caused it to overbalance, pivot on the front edge of the sledge, and rotate through 70 degrees. As this happened, the 6 tonne bundle of stones slid off the end of the stone (Fig. 6) onto the ledge in the stone-hole in front (Fig. 7), the sledge broke away from its lashings and the stone neatly dropped into the hole.

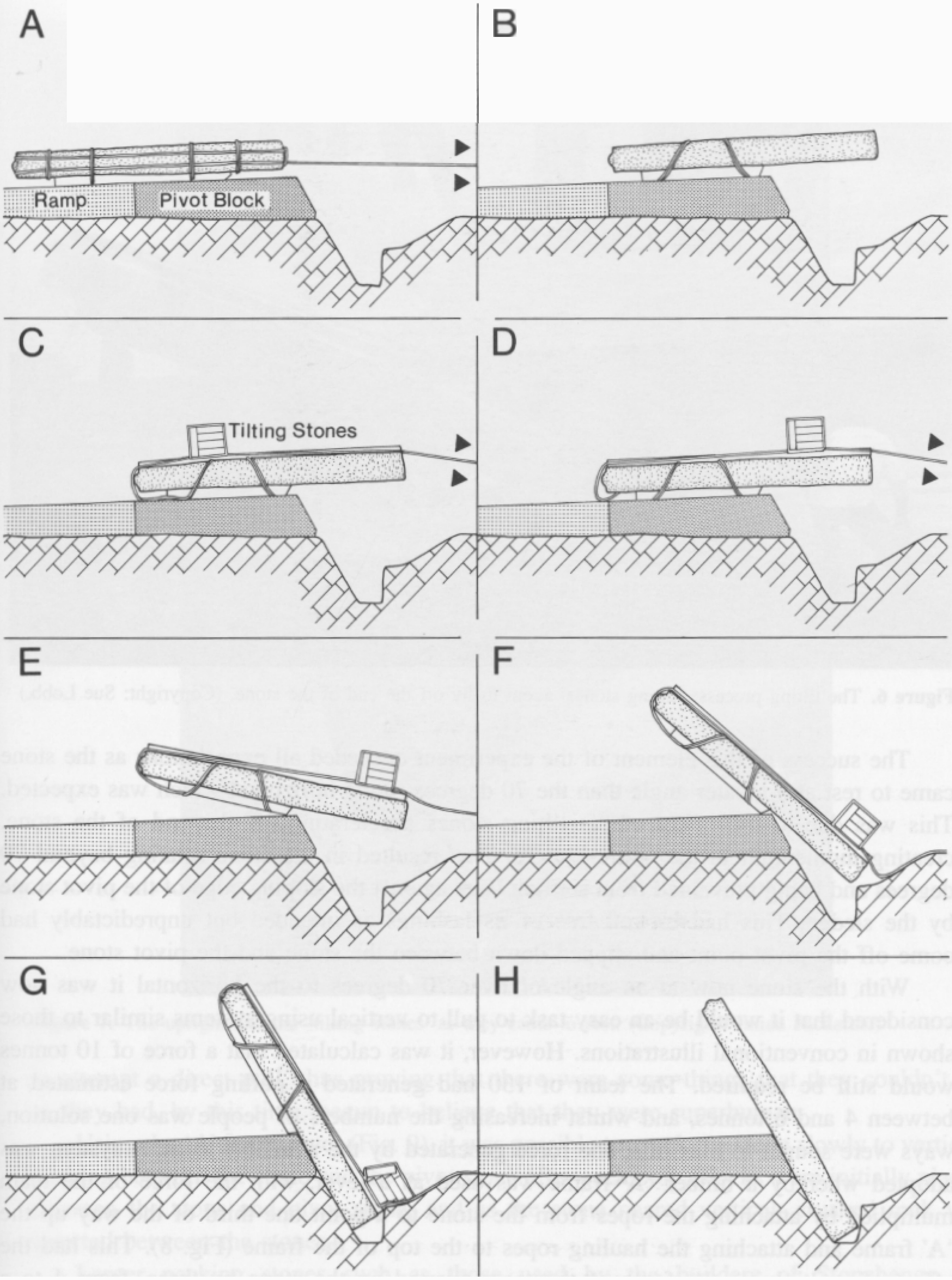
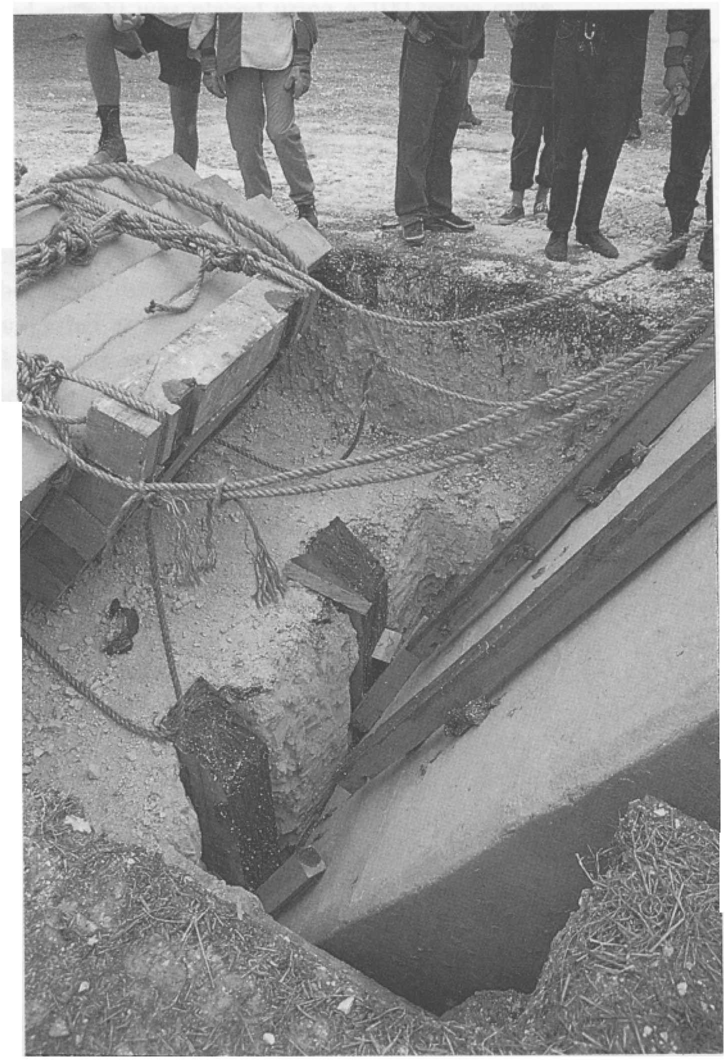


Figure 5.

Figure 6. The tilting process; 'tilting stones' about to fly off the end of the stone. (Copyright: Sue Lobb.)

The success of this element of the experiment exceeded all expectations as the stone came to rest at a greater angle than the 70 degrees to the horizontal which was expected. This was due to the effect of the tilting stones accelerating off the end of the stone, creating momentum in the entire system. This resulted in the stone rotating beyond 70 degrees and being prevented from settling back against the sloping edge of the pivot stone by the sledge. This had broken free of its lashings as intended but unpredictably had come off the pivot point and slipped down between the stone and the pivot stone.

With the stone now at an angle of over 70 degrees to the horizontal it was now considered that it would be an easy task to pull to vertical using systems similar to those shown in conventional illustrations. However, it was calculated that a force of 10 tonnes would still be required. The team of 130 had generated a pulling force estimated at between 4 and 6 tonnes, and whilst increasing the numbers of people was one solution, ways were sought to maximise the force generated by the available team. A system was adopted whereby a timber 'A' frame was used as a lever, witn the force of the team multiplied by attaching the ropes from the stone to a point one third of the way up the 'A' frame and attaching the hauling ropes to the top of the frame (Fig. 8). This had the effect of multiplying the force of the team exerted on the stone by three, from 4 to a maximum of 12 tonnes. Before the team could put this into effect, they were allowed



igure 7. The upright and the 'tilting stones' as they came to rest. (Copyright: Julian Richards.)

attempt a direct pull, thus proving that there were some things that they couldn't do s they had, by this time, begun to believe that they were superhuman.

Using the 'A' frame lever (Fig. 9), it was possible to crank the stone slowly to vertical, acking between the stone and the pivot stone after each pull. Blocks were initially placed etween the stone and pivot stone, and as the stone neared vertical, crushed rock was serted between the stones.

Larger packing stones such as those used by the builders of Stonehenge are ore practical as a packing medium than using crushed stone as the latter can escape

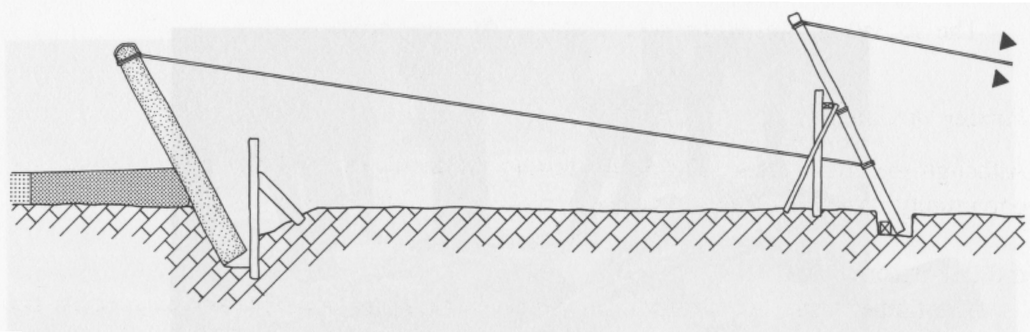


Figure 8.

Figure 9. 'A' frame used as a lever to assist with the pull to upright. (Copyright: BBC.)

around the side to the front of the stone, frustrating attempts to raise it to a vertical position.

A useful function of the steepness of the rear face of the stone-hole is that it leaves a small wedge to be infilled, much more able to hold the stone upright than a hole with a shallower face. There is also less tendency for the fill material to escape as the stone tips back against it.

The second upright was placed using a 100 tonne crane.

Raising the lintel

Although the engineering solution for raising the lintel involved the use of a ramp, the opportunity was also taken to test the conventional 'crib' method.

CRIB METHOD

The timber 'crib', essentially a platform of alternating horizontally laid timbers, has often been suggested as the method by which the lintels were raised. Some illustrations show a plank decking on which workers use levers to raise alternate ends of the lintel, which are then supported before the process continues. This method was tested using a platform of railway sleepers (Fig. 10) and demonstrated that the lintel could be raised quite satisfactorily. Each end of the stone could be raised by the depth of a railway sleeper (approximately 150 mm). The process of levering was shown to be quite easy and swift, with considerably more time being taken to raise the remainder of the platform up to the corresponding level. Once the platform had reached a height above which a direct downward pull could not be applied to the ends of the levers, then they could only be operated by means of ropes. Operated in this way the levers were prone to slipping. The

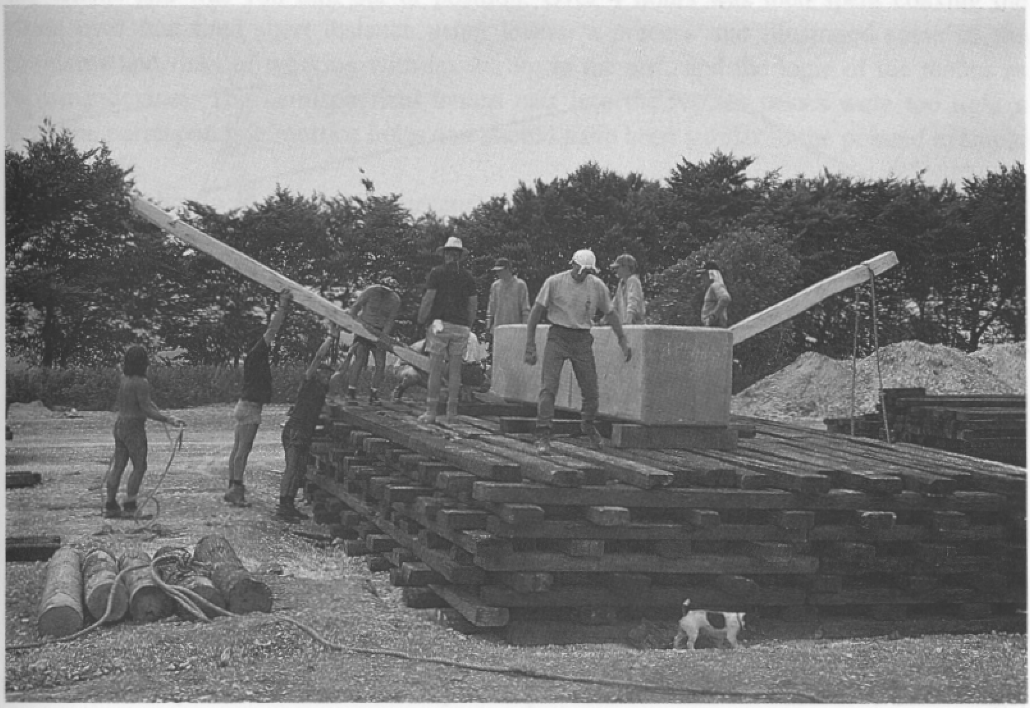


Figure 10. The use of the timber 'crib' and levers to raise the lintel. (Copyright: Julian Richards.)

consequent risk to their operators could have been minimised either by notching the levers where they passed over their pivot blocks, or by employing safety ropes to prevent them falling from the platform. The advantages of this method lie in its comparatively simple material requirements and in the ease with which the platform can be erected and dismantled for reuse. The construction of a platform of sufficient size to provide an adequate and stable working surface (say 9 m long and 3 m wide to a maximum height of 6 m) would require approximately 2600 m of timber of square section or diameter 250 mm. The squared timber could be provided by approximately 200 trunks 4.5 m long and 1 m in diameter while the round section timber would be easier to obtain and work and, if rudimentarily notched, would create a structure of some stability. Whatever section the constituent timbers, the structure could be stabilised by tying it in through the gap between the upright sarsens.

RAMP METHOD

The method devised for raising the lintel (Fig. 11) is essentially a variation on the ramp method suggested by a number of previous authors (e.g. Stone 1924a) and tested at a considerable scale by Pavel (Pavel 1992). A 30 degree scaffolding ramp was constructed, intended to represent one built of timber and earth, but with due regard to

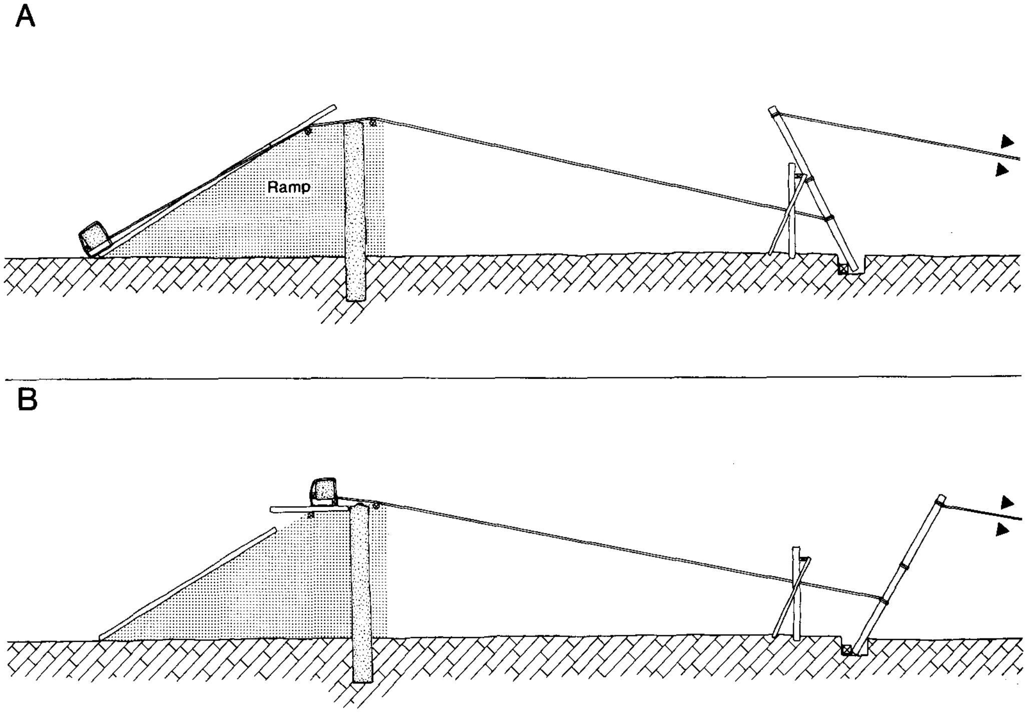


Figure 11.

health and safety. A slipway of three parallel wooden rails (similar to those used in the preceding elements of the experiment) was built on the ramp up which the lintel was to be hauled, lashed to a sideways running wooden sledge. The sledge was that used for the raising of the upright, now running at 90 degrees to its original direction of travel and consequently with additional notches cut to engage the three rails. At the point at which the angled ramp joined the horizontal decking around the top of the uprights, the final section of the rails projected the 30 degree ramp angle. The rails here were designed to break as the stone reached this point, allowing it to slide the final horizontal distance of 1.5 m into a position just in front of the two uprights. The level of this was such that it was set to clear the top of the tenons on the upright stones, by running off the slipway onto two greased blocks set on top of the stones.

It was calculated that the force required to haul the 10 tonne lintel up the greased slope of 30 degrees was approximately 6 tonnes, achievable with the full team of 130, who, using the 'A' frame lever, had generated a pulling force of 12 tonnes. Using the same system and with a reduced team of 90 people (this was the third weekend and numbers were falling), the lintel on its sledge was hauled up the ramp, at each stage being tied back and the 'A' frame reset (Fig. 12). Once teething problems with both lashing and with the sledge binding on the rails had been overcome, the lintel was raised in about 3 hours. However, in pulling up the ramp, the lintel had drifted out of line with the tenons and was 100 mm out of position. Over 4 hours was then spent coaxing the stone over that final short distance using levers, a process that illustrated some of the problems and risks of working with levers 'up in the air', and the logic of the tenons as locating devices. The hemispherical tenons cast into the replica stones were too tight a fit in the corresponding mortice holes and should have been similar to the pointed example on stone 56.

The trilithon was then complete and the removal of the ramp allowed the scale of the complete structure to be appreciated (Fig. 13). Even allowing for the fact that stone 55 never possessed the grace of its companion upright the completed trilithon was a structure of considerable power and elegance.

Conclusions

Julian Richards & Mark Whitby

The results and validity of the experiments

The experiments, inevitably involving some moments of anxiety and carried out with the awareness that the end product was intended to be a television programme, were both enjoyable and informative. Between engineer and archaeologist some divisions of opinion were identified and some remain amicably unresolved. While not suggesting that the methods devised and implemented were the only ones possible for the construction of Stonehenge, alternatives to the standard orthodoxy have been devised, tested and proved feasible.

Figure 12. The use of a ramp to raise the lintel. (Copyright: Julian Richards.)

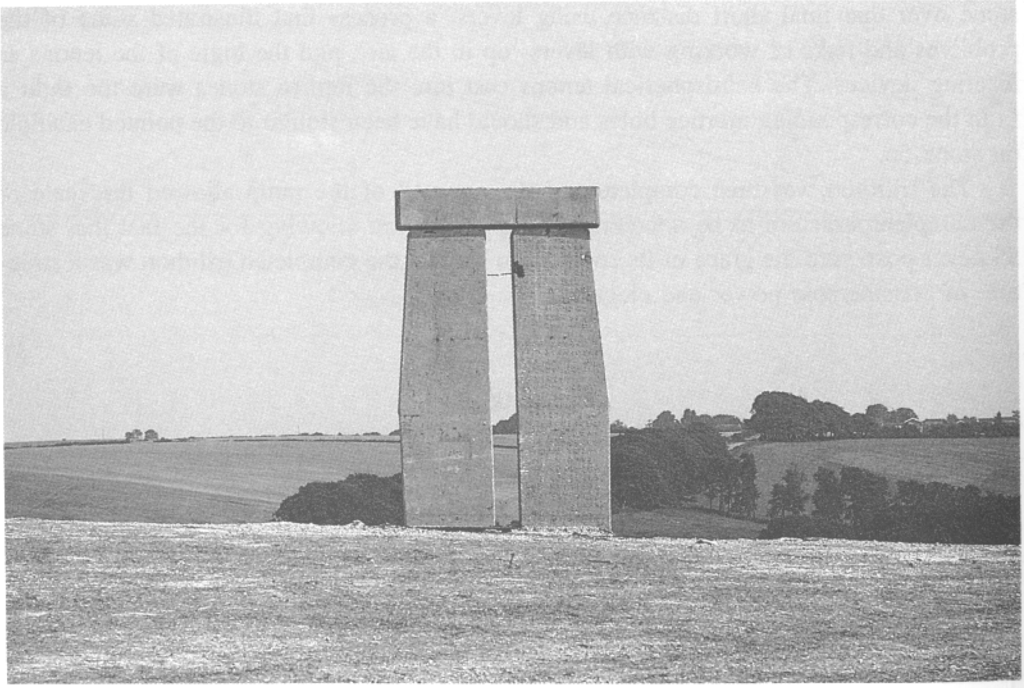


Figure 13. The completed trilithon. (Copyright: BBC.)

It has been clearly demonstrated that a 40 tonne load (one major upright or three or four lintels) can be moved up a slope of 1 in 20 with a minimum labour force of approximately 130. Allowances for the lower friction coefficient resulting from the use of lubricants available to the original builders suggest that the motive power of approximately 200 individuals would be required. The experiment demonstrated that movement down a 1 in 20 slope required only 60 individuals, suggesting that approximately 100 would be a more realistic ‘prehistoric’ figure. Many previous theoretically derived estimates of human power requirements now seem to have been over cautious and there seems no reason why alternative methods of transportation should not produce similar figures to those derived from the recent experiments.

What was required by this task, and by the other elements of the experiment described above, was a considered approach to the problem to be solved and an investment in infrastructure. Both the sledge and the rails are simple, robust and capable of reuse, their construction well within the capabilities of Neolithic woodworkers. It could be argued that continued use would improve the efficiency of the combined sledge and rails and that the recent experiment was carried out during the ‘running in’ period of the replicated equipment.

The solution devised for the raising of the upright may, to some, be seen as over complicated, or perhaps over engineered. There are sound reasons, however, why the method currently most frequently presented in graphic form requires reappraisal and the recent experiment introduced only one novel concept, that of the employment of weights to assist with the tilting process. The requirement for some form of ramp to elevate the bottom end of the stone to be erected has previously been recognised and a logical extension of this requirement is the provision of a solid pivot point to provide additional control as the stone swings over. The leading edge of an earth ramp would not provide sufficient rigidity and, although this could be provided by a substantial timber revetment, one made of stone would perhaps be more stable.

Moving the upright to vertical from its position of rest within its stone-hole may seem the simplest part of the overall process, but proved difficult. These difficulties, and the necessity of employing an ‘A’ frame to multiply the effort applied on the ropes, demonstrated that insufficient direct force could have been applied by employing shear legs as often suggested. The Spanish windlass (involving twisting paired ropes by means of a pole inserted between them) which was required in order to take up slack in the ropes may be unnecessary if ropes are stretched and appropriately treated before use.

The two methods of raising the lintel, ramp and ‘crib’, were both shown to work, although only the former was carried through to completion. Other methods should now be evaluated in terms of their material and labour requirements.

Implications for labour requirements (J.R.)

The experiments described above addressed parts of the overall task of building one element of Stonehenge. They have provided the first data empirically derived from the movement and erection of full-sized components, data which should consequently be capable of providing a greater insight into the labour requirements of the monument as a whole, or at least for the sarsen structures. The intention of estimating labour requirements is not to attempt to inject some false precision into the overall monumental task, but rather to place it in perspective with contemporary structures and to suggest a reasonable time frame within which it could have been completed.

The building of the sarsen structures which, although now redated, are essentially the 'Beaker Monument' discussed by Startin (1983), involves a number of identifiable tasks, each with its own specific problems, solutions and consequent labour requirements.

EXTRACTION

Stones at their source, to judge from surviving but possibly atypical examples, would have required not quarrying but possibly partial excavation to free them from their surrounding matrix of colluvial deposits and soil. A direct lift or sliding a short distance would then have been required in order to place them on the sledge. The excavation and lifting/dragging, activities focused on a specific area, would have required large numbers of people for short periods of time. Alternatively, this task would have been made considerably less labour intensive if the stones had already been selected, extracted and possibly raised for use in an existing structure. The Avebury area is certainly one in which there was, by the Later Neolithic, some experience of moving and raising large stones, for example those used in the construction, if not the blocking, of the West Kennett long barrow (Piggott 1962).

TRANSPORT

Without a precise understanding of the route from the source of the sarsens (at *c.*150 m OD) to Stonehenge (at *c.*100 m OD) it must suffice to say that the route undulates. It has been demonstrated that moving the largest of the stones uphill would have required approximately 200 people, while easier gradients and smaller stones will obviously lessen the labour requirement. It therefore seems likely that, if a team of 200 is required for specific aspects of the transportation process, a team of this size would have been available throughout. Averaging gradients suggests that a 40 tonne stone could be moved over 30 km in 12 days with 200 people, perhaps less time with the trackway installed for the complete route. The possibility that the route was not only defined but that rails or alternative structures were laid for its entire length should not be discounted. The material requirements can be placed in context by those estimated for the construction of the timber platform to raise the lintel (above p. 246) and by the quantities of timber used in broadly contemporary monuments in the Avebury area. Here the construction of the West Kennett palisade enclosure (Whittle 1991) demonstrates no shortage of mature timbers and, as already noted, the route itself provides a corridor along which timber resources were presumably widely available. A continuous track does not seem impossible in the context of Neolithic trackway construction in the Somerset Levels (Coles and Coles 1986) and would allow for the movement of several stones simultaneously, using the full complement of 200 to move the largest stone where gradient required such effort, splitting into smaller teams to move additional stones on easier gradients. There may be advantages in a smaller stone travelling in convoy with a large example as the former could be used to overcome the sticking effect shown to bind sledge to rails when at rest, effectively to 'bump start' the larger stone.

If it is accepted that unquantifiable but not excessive time is spent in preparing the infrastructure for transport, then the figure given above for the movement of a single 40 tonne stone can be used to calculate that the 80 or so sarsens, with a combined unshaped weight of at least 1300 tonnes, could have been moved in approximately 100,000 person/days. If 200 people is the optimum team size then 500 days would have been required suggesting that the stones could have been transported within two years, or, if transportation was a part-time, possibly seasonal activity, comfortably within a decade.

The components of the sarsen structures at Stonehenge show a remarkable uniformity of scale and proportion, even if some has been achieved through careful tooling. It seems inconceivable that the building of the structures was started before the stones had all been selected and most likely transported to site. This seems to suggest a concerted short period of prospection, identification, extraction and transport.

SHAPING

This aspect of the overall task was not addressed by the recent experiments and remains one of the most difficult to quantify in terms of both method and labour requirement. The accepted method of shaping is by means of stone hammers or 'mauls' but whatever the method employed, the volume of material removed in the case of each stone is incalculable as consequently are the labour requirements.

RAISING

At Stonehenge itself the requirements for both resources and labour would have been concentrated although the latter could have been considerably reduced by employing methods similar to those demonstrated in the recent experiments.

Once delivered to site, the majority of the required effort would have been directed towards the preparation of stone-hole and ramp, positioning the stone and installing the ropes and mechanisms for tilting. The availability on site of a range of sizes of sarsens, and, at this time, the bluestones, would have facilitated a number of tasks. Ramps could have been built around a core of stones, firmer and easier to move into place and subsequently remove than volumes of earth or chalk.

The preparation, tilting and hauling to upright could have been achieved by a maximum team of approximately 150 people (the number required to pull the largest stones to vertical). Given the variety of scale and duration of the constituent tasks within this phase of the buildings programme, a team of this size could probably have accomplished the raising of all of the uprights within a period of 120 days (18,000 person/days).

PLACING THE LINTELS

The labour requirements for this task depend on the method employed. Considerable effort is required for the construction of a ramp, although once in place the lintel can be raised quickly, certainly within a single day, by around 90 people. In contrast, the crib requires little preparation once the timbers are available, but is a slower process, taking a team of around 20 people one day to raise each lintel a distance of 1 m. Using the lowest labour requirements, the raising of the 35 lintels can be estimated as having taken a team of 20 145 days (2900 person/days).

OVERALL REQUIREMENTS

What is suggested by the figures above is that, given a tremendous concentration of effort, the sarsen structures at Stonehenge could have been built within a period of 3 years. Such a short time scale seems unlikely as the construction of a monument such as Stonehenge cannot have been an impulsive gesture and must have involved considerable planning and social organisation. The 200 individuals estimated as being required for the most focused and labour intensive of the tasks represent the undeniable element of a labour requirement that may be far more substantial and extensive. The building of Stonehenge provides evidence of an extraordinary degree of social cohesion and of co-operative effort on more than a local basis. Its stones, both sarsens and the bluestones now accepted as having been deliberately transported from the Presceli mountains (Green, this volume; Scourse, this volume) show a monument of national significance at the time of its construction.

Stonehenge as construction site (J.R.)

It is unlikely that the scale and intensity of construction at Stonehenge would have left no physical trace. Within the earthwork enclosure the timber settings, only recently documented in a comprehensible manner and interpreted largely within the intellectual framework imposed by Stonehenge (Cleal *et al.* 1995, 140–52) may have had a more prosaic function. The profusion of predominantly unphased post-holes within the stone settings cannot all be organised into convincingly circular ceremonial structures (op. cit., fig. 70). Phase 2 includes both the timber settings on the main causeway (op. cit., figs 67–8) and evidence of 'the deliberate backfill of some parts of the ditch with clean chalk' (op. cit., 115). Phase 3 involves the introduction into the ditched enclosure of around 1300 tonnes of sarsen, together with the smaller bluestones, but from which direction? If in the direction in which they were to be raised then they would either have to be introduced over the ditch and bank or manoeuvred within the enclosure. The former would seem more practical but would involve temporary backfilling of the ditch and a coincident breaching of the bank. There appears to be evidence of the former and the bank has been insufficiently examined to identify breaches and subsequent reinstatement. The other possibility is that either for practical or ceremonial reasons, the main entrance was utilised. This would have required reinforcement of the fragile causeway in order to prevent its eventual erosion. Can the timber settings on the causeway be interpreted as the remains of post-based plank surfaced bridging structures or are they simply ceremonial? The evidence is ambiguous, but alternatives to monotheistic interpretations should also receive consideration.

The future direction of experimentation (M.W. & J.R.)

The constraints of experimentation within a filming schedule inevitably meant that many avenues of research were identified but not followed. Alternative vehicles and tracks for stone transport may be suggested and studies of lubricants should examine the properties of a wide range of substances available in prehistory. Experiments in rope making should continue and should involve the use of other types of fibre. Other methods of raising the uprights may be suggested, while those appropriate for raising the lintel continue to provoke debate amongst the authors. While one (Richards) still favours the timber crib method, the other feels that a variation of the method described by Hogg (1981) may be quicker and more efficient. Hogg suggests rocking stones about a central pivot placed between the paired uprights (Fig. 14), a method which in principle is described as being used in the construction of pyramids (Fitchen 1986, 230).

The methods of construction employed at Stonehenge will no doubt continue to exercise the imagination of both archaeologists and engineers. It would be preferable if their practical skills could also be exercised. After the completion of the experiment the trilithon was dismantled (by crane) and its components were donated to English Heritage. They are currently (1996) in store on the Salisbury Plain Training Area. Their fate is undecided but it has been assumed that they will eventually be re-erected at an appropriate venue. Far from being a static monument to a single experiment, the authors would prefer to see the replica stones used in a dynamic way, available for further experimentation to anyone with an idea to test and the resources to carry it through in safety. The stones are unlikely to be replicated again in a manner suitable for robust use and once permanently raised both they and the ideas that they generated will end up set in concrete. An annual Stonehenge trilithon raising (preferably timed for completion on 21st June) could also prove to be a considerable visitor attraction.

Postscript

'The engineer who designed Stonehenge, and devised the methods by which the work of erection might be carried out, must have been a man of extra-ordinary ability – the Archimedes

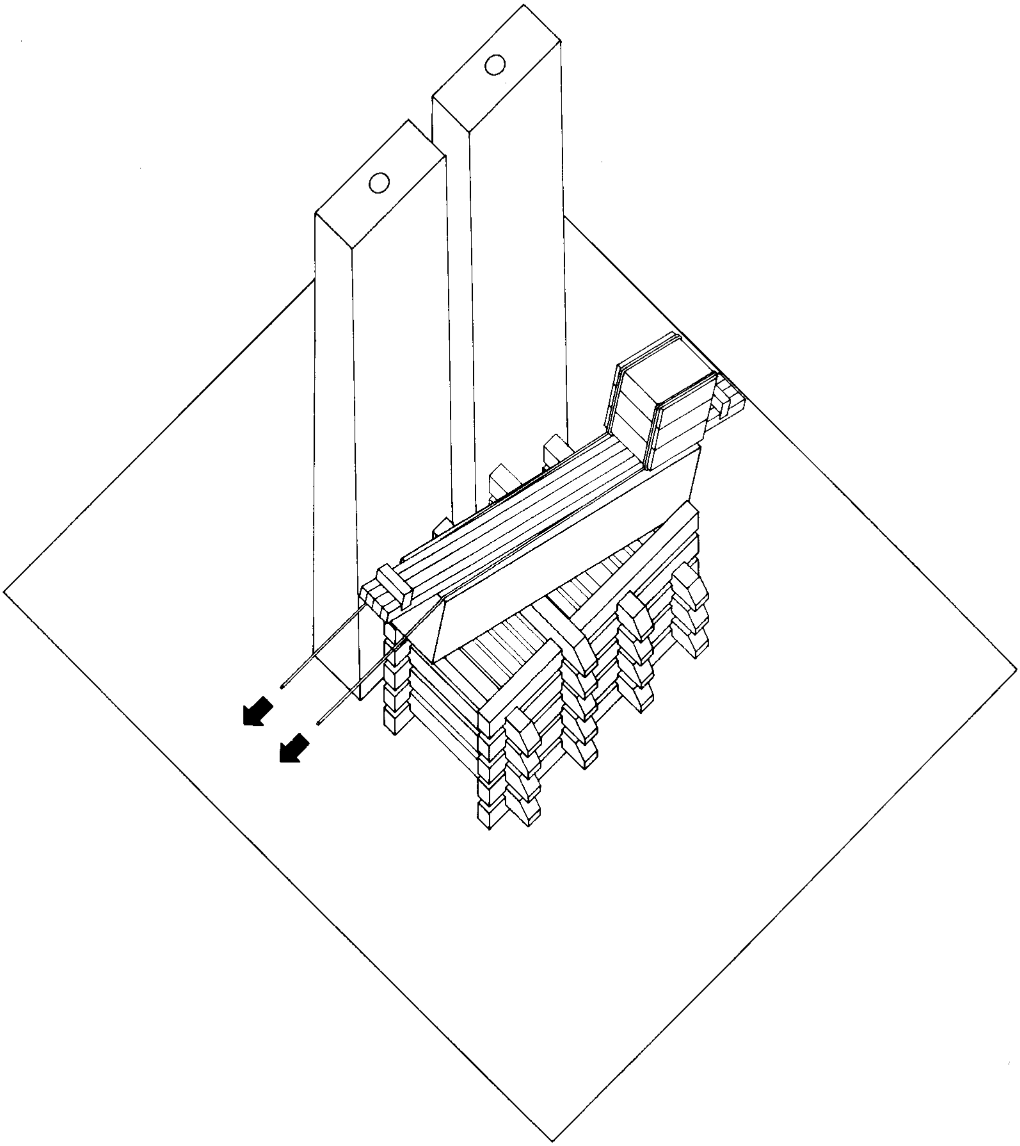


Figure 14.

of his time... He was perhaps the man from whom the legend of Merlin had a remote origin ... He was probably a foreigner – "a wise man from the east" (Stone 1924a, 447).

The experiments described in this paper are of the late twentieth century, a time when the overwhelming force of the machine age appears to have rendered obsolete the skills and ingenuity of our forbears. Those involved in the experiment feared that any degree of success would somehow diminish the achievements of the original builders, or contribute to a gradual demystification of Stonehenge. This was far from the case. The experiments gave all who participated, and, it is to be hoped, the viewers of the television programme, an increased respect for those who laboured with antler picks, split timbers, twine ropes and maybe unwilling beasts, to construct the most enduring and celebrated achievement of our prehistoric past.

Acknowledgements

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meaning that underpinned those beliefs. Physical and celestial 'markers' were used at different periods to articulate meanings relative to the use and social significance of space, both within the monument and in the surrounding landscape. Four phases to these changes are proposed, each identified with a series of structuring principles: linear binary, linear quadruple, radial concentric, and linear concentric. All four phases are marked archaeologically by a re-design of Stonehenge and the restructuring of space around about.

CLIVE RUGGLES

Astronomy and Stonehenge

This paper begins by making some general observations about the perception and use of celestial phenomena in prehistoric times, what exactly is meant by 'astronomy', and why the prehistorian might be interested in it. We then proceed to establish a conceptual framework for studying prehistoric astronomy, identifying possible horizon 'targets' for symbolic alignments (which are less precise, fewer, and different in nature from those very often assumed), and explaining the significance of declination. This is followed by a critique of recent ideas about astronomy in and around Stonehenge, in the light of the newly published reports of twentieth-century excavations. The paper concludes with a summary of what we can begin to say with reasonable confidence about the nature and meaning of astronomy at Stonehenge, and presents some suggestions for the future research agenda at and around the site.

JULIAN RICHARDS and MARK WHITBY

The engineering of Stonehenge

A series of practical experiments, carried out at the instigation of the BBC, involved the transport and erection of the individual components of a full-scale replica of the Great Trilithon at Stonehenge. The use of a simple sledge running on a greased timber track demonstrated that a 40 tonne stone, representing one of the uprights, could be moved up a 1 in 20 slope using the motive power of 130 individuals. The raising of this stone to vertical was accomplished by rotating the stone over a solid pivot point with the assistance of a composite 6 tonne weight running along its length. An angle of 70 degrees to the horizontal was achieved by this method and the stone was hauled to vertical using a timber 'A' frame as a lever. The lintel was raised on a sledge running on rails up a ramp although a comparative experiment demonstrated that the orthodox timber 'crib' or platform provided a viable alternative method. For the purposes of all experiments a degree of proficiency in both woodworking and the manufacture of rope was assumed.

The overall labour requirements for the building of the sarsen structures at Stonehenge are recalculated from the newly available data. In addition, alternative interpretations of some elements of the physical record of Stonehenge are offered and suggestions are made for the future direction of experimentation.

C. P. GREEN

The provenance of rocks used in the construction of Stonehenge

The geological evidence in Wiltshire gives no support to the view that the stones forming Stonehenge were found by its builders close to the site of construction. The presence of suitable sarsen stones near Stonehenge in the Early Bronze Age is indicated neither by the geological history of the area nor by the present-day distribution of sarsens. The absence of glacial or glacially-derived material on Salisbury Plain makes it unlikely that glacial ice carried the bluestones of Stonehenge from the Preseli Hills to Wessex. The history of the bluestone supposedly found in Bowls Barrow is reviewed.

J. D. SCOURSE

Transport of the Stonehenge bluestones: testing the glacial hypothesis

Two principal mechanisms have been invoked to explain the transport of the far-travelled bluestones used in the Stonehenge monument from their source region in Pembrokeshire: by glacier or by man. Glaciers have been thought to represent the only natural agency capable of transporting boulders of the size of the bluestones over the distances required, and this mechanism has periodically received serious attention since it was first proposed by Judd in 1902. There are two current propositions invoking transport of the bluestones by ice; Thorpe *et al.* (1991) envisage Anglian ice flowing eastwards from Pembrokeshire across South Wales and into central southern England, whilst Kellaway (1991a, 1991b) suggests deposition from the north in association with a Pliocene glaciation at 2.47Ma. The glacial hypothesis is critically tested by addressing four issues: the physical principles underlying the entrainment and transport of large boulders by glaciers; the occurrence/absence and implications of diagnostic surface microwear and particle shape characteristics of the bluestones; the Pleistocene stratigraphy and geomorphology of southern England and adjacent shelves; and the glaciological plausibility of a source trajectory from Pembrokeshire. It is demonstrated that though glaciers are capable of transporting erratic boulders many thousands of kilometres irrespective of bed topography, the particular case posed by the Stonehenge problem is not compatible either with the mechanics of ice flow or with the geological evidence. The weight of the current available evidence strongly indicates that the Stonehenge bluestones were not transported by ice from Preseli to Salisbury Plain.