Compute-intensive GIS visibility analysis of the settings of prehistoric stone circles

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1 The past and future of GIS-based visibility analysis

For twenty years visibility analysis has been one of the most popular archaeological applications of geographical information systems (GIS) for interpretive purposes. In 2003 Lake and Woodman (Lake and Woodman 2003) provided a detailed account of the various forms that GIS-based visibility analysis had taken up to that time. They argued that such analyses could be divided into those that were predominantly informal, statistical, or humanistic, and furthermore, that this tripartite division recapitulated—albeit over a compressed timescale—theoretically driven developments in non-GIS visibility studies. Nearly ten years on it is probably safe to say that all three forms of GIS-based 'viewshed analysis' have lost their novelty value. Thus informal viewshed analyses, those that lack statistical or theoretical sophistication and adopt a largely 'common-sense' approach to inference (Lake and Woodman 2003) are no longer found in methodological literature but are scattered through the relevant subject literature. More interesting is the lack of evidence that more sophisticated statistical or humanistic analyses routinely contribute to archaeological explanation / interpretation (but see Gillings 2009 for a recent exception). We suspect that the increasing ubiquity of multi-core processors—and the power of modern desktop computers more generally—will lead to a resurgence of interest in GIS-based visibility analysis. To see why this might be so, it is worth revisiting the distinction between statistical and humanistic GIS-based visibility analyses and to consider how the failure of either approach to become a routine part of landscape archaeology was in no small part due to computational limitations.

Statistical studies of visibility, those characterised by an explicit concern with quantification and inferential rigour, pre-date the archaeological application of GIS and may in a general sense be considered examples of Processual archaeology (Lake and Woodman 2003, p.690). In an European context, the influence of the New Geography, as expounded in Haggett's (1965) *Locational Analysis in Human Geography*, is clearly seen in Fraser's later (1988) work on study of visibility from Orcadian Neolithic chambered cairns and in a number of other studies (e.g. Barnatt and Pierpont 1983; Bradley et al. 1993a,b; Ruggles et al. 1991) which, while not always explicitly subscribing to, nevertheless supported the prospects for a so-called Cognitive-Processual archaeology (Renfrew 1982, 1994). What all these share with subsequent GIS-based statistical visibility analysis (e.g. Ruggles and Medyckyj-Scott 1996; Wheatley 1995, 1996; Fisher et al. 1997; Lake and Woodman 2000; Woodman 2000) is the use of a control sample to ascertain whether the viewshed properties of the archaeological sites in question could have occurred by chance alone or were more likely to reflect the intentions of past people (Lake and Woodman 2003, p.693). The most sophisticated of these (e.g.Fisher et al. 1997; Woodman 2000) used Monte Carlo simulation and stratified random sampling in an attempt to distinguish association from causation, in other words, they sought to ensure that apparently significant viewshed properties of archaeological sites were more than simply a by-product of other locational choices such as elevation.

The humanistic turn in archaeology (see, for example, Hodder 1986 and Shanks and Tilley 1987) produced a number of visibility studies that frequently share the Cognitive-Processual interest in ideology and cognition, but which often place greater emphasis on the non-discursive knowledge of past people. These studies are typically characterised by a concern with situated visibility—the changing field of view as one moves through a landscape or archaeological site—and, perhaps inevitably, they usually focus on the particular rather than the general. The phenomenological approach of Tilley and his co-workers (Tilley 1994; Bender et al. 1997, 2007; Tilley 2004) has been particularly influential, but there are others, such as Barrett (1994, pp.15–17) and Thomas (1993, p.42), who have shown greater interest in visibility as a resource for the maintenance of power relations and social reproduction. Much archaeological writing in a humanistic vein has explicitly questioned conventional scientific reasoning (see papers Edmonds et al. 1990, also Thomas 2004), but recently there has been renewed interest in the development of methodology to permit a degree of repeatability (Hamilton et al. 2006). The mid 1990s witnessed a bout of soul searching in which leading proponents (e.g. Wheatley 1993, p.133) of archaeological GIS expressed their fear that the uptake of GIS either wittingly or unwittingly encouraged a functionalist approach to archaeological explanation that they felt had otherwise been largely rejected as part of the humanistic critique of Processual archaeology. In many respects the ensuing critique of archaeological GIS reflected the wider post-Positivist critique of GIS in geography, incorporating both ontological (see e.g. Thomas 1993 c.f. Sui 1994) and epistemological (see e.g. Gaffney et al. 1996, p.132 c.f. Wright et al. 1997) concerns. Lake and Woodman (2003, pp.694–5) provide a detailed account of the charges laid against GIS-based visibility studies. For present purposes it is sufficient to note that the response was ultimately a focus on ‘perception’, whether by attempting to compute more nuanced forms of viewshed such as so-called Higuchi viewsheds (Wheatley and Gillings 2000), or to compute visual landscape ‘affordances’ *sensu* Gibson’s (1986) ecological theory of perception (primarily the work of Llobera (2001; 2003; 2007)), or the call for greater awareness of the interconnectedness of sensory experience (Freeman and Gillings 2007) and possibly the use of virtual reality (Gillings and Goodrick 1996).

By the turn of the millennium the state-of-the-art in GIS-based visibility analyses was such that any substantive contribution to a real archaeological problem (as opposed to a case study intended only as an illustration of method) would require substantial computing resources. This was equally true of both the statistical approach, with its use of control samples and in particular Monte Carlo simulation, and the humanistic approach, whose emphasis on visual affordances would require the computation of viewsheds for entire landscapes (so-called ‘total viewsheds’—see Llobera 2003), or which would alternatively require the construction of virtual reality models. We suspect that goes some way to explaining the relative paucity of sophisticated and inferentially successful GIS-based visibility analysis over the past ten years. The point is not so much whether the necessary computational resources could be found at all—Exon et al’s (2000) intensive study of the intervisibility of barrows in the vicinity of Stonehenge and Llobera et al’s (Llobera et al. 2010) use of the Condor high throughput computing framework demonstrate the possibility of such studies—, but whether they were or were perceived to be available in the context of primarily subject-focussed archaeological projects. It is our contention that the power of desktop computers has now reached the point where some of the more sophisticated forms of analysis proposed as many as ten years ago can now be more routinely used ‘in anger’, that is, to draw inferences from real data sets rather than simply to illustrate methods on ‘toy’ data sets. Coupled with the development of a more eclectic and less sharply polarised theoretical climate (Pearce 2011) we anticipate that this will lead to a renewal of interest in, on the one hand, large scale generalising comparative visibility analyses where the lack of subtlety of traditional GIS-based visibility is less problematic and, on the other, the merging of GIS-based visibility analysis with the use of augmented reality (Eve in press), in this case precisely to overcome the lack of subtlety required for particularising studies. In the remainder of this chapter we provide an example of the former approach, made possible by the use of adaptive parameterisation of the viewshed calculation.

2 The visual setting of stone circles

The particular problem we address in this chapter concerns the visual setting of stone circles. The prehistoric stone circles found across many parts of Great Britain and Northern France were constructed between the Middle Neolithic and Late Bronze Age (*c.*3500 BC–1000 BC), although the form re-emerges in Scandinavia and North East Europe from the late Iron Age (500+ BC). Here we are concerned with British stone circles which, despite disagreement about their exact definition (see Barnatt 1989, p.505 contra Burl 2000, p.317 and Bradley 1993, p.55 in the case of Avebury) basically comprise a number of large stones or boulders (orthostats) arranged as an ellipse, although their size and form vary considerably with time and from region to region: the diameters of the British stone circles studied in this chapter range from 1.5m to 350.6m and the estimated original numbers of stones from 4 to 99 (data from Barnatt 1989.

Stome circles are among the most enigmatic of prehistoric monuments and their purpose is not certain. First described in detail by the early Antiquarians Stukeley (1687–1765) and Tolland (1670–1722), who thought them to be ‘Celtic’ Druidic temples Burl 2000, p.16 they have more recently been explained as places of assembly (Harding and Lee 1987) and / or instruments for calculating and predicting the seasons or the movement of the sun or the moon (Hawkins 1966). Their form has likewise been attributed to various forces, ranging from the punishment of wrong doers resulting in circles of petrified beings (folk tales reported in Burl 2000, p.69 to their careful layout employing a standard unit of measurement known as the megalithic yard (Thom 1967). Explanations for the location of stone circles are equally varied and include: coincidence with the path of ley-lines forming a telepathic network across the landscape (Williams 1968); the actions of prehistoric water diviners (Underwood 1969); centrality within hierarchically organised territories (Renfrew 1973); orientation with respect to the movement of celestial bodies (Thom 1971; Ruggles 1999) and most recently the symbolism of the setting (Bradley

1998; Richards 1996). It is attempts to explain location in terms of visibility which interest us here.

The idea that stone circles functioned as *high-precision* astronomical instruments has been largely discredited by a number of studies (Ruggles 1984; Ruggles and Burl 1985; Ruggles et al. 1991; Barnatt 1989; Barnatt and Pierpont 1983) which have, nevertheless, confirmed that many stone circles are indeed oriented with reference to astronomical events. The finding of these broadly Cognitive-Processual studies that astronomical alignments—while real— were of rather lower precision than once supposed has informed a humanistic strand of interpretation, one which takes a more experiential approach to stone circles (Watson 2001, p.307). At their most ambitious such interpretations combine the solar and lunar orientation of stone circles with insights from ethnographic analogy to posit that stone circles such as Stonehenge and Avebury were part of complexes of monuments which ritualized an understanding of the human lifecycle as one involving life, death and rebirth (Pearson and Ramilisonina 1998; Bradley et al. 2005).

Less ambitiously, and focussing more on terrestrial visibility, it has been noted that stone circles are not necessarily prominent in the landscape and may have been difficult to locate from both nearby and from far away (Bradley 2002, p.75), especially when compared with burial monuments which were often built of materials providing high visual contrast with the immediate environment (Burl 1988, pp.47–50). Consequently, some have argued for the importance of concealment as a means of effecting social differentiation in the experience of rituals taking place within stone circles (Barrett 1994, pp.15–18, Bradley 1993, p.53, Thomas 1993, p.42). This concern with visibility looking in towards stone circles is mirrored by an interest in the terrestrial view out, notably in the work of Bradley (1998) and Richards (1996), both of whom have examined prehistoric monuments in relation to their landscape setting. Bradley characterises the locations of certain stone circles as embodying a “circular perception of space” (Bradley 1998, p.122), citing as examples Castlerigg stone circle, which is situated with “a facade of standing stones confronting a chain of mountains”, Long Meg and Her Daughters which commands a “virtually continuous horizon of hills and mountains” and Avebury, which he describes as being “ringed by a horizon of hills” (Bradley 1998, p.122–3). Richards notes that while being almost surrounded by water due to its location on an isthmus, the Ring of Brodgar is nevertheless "enclosed by the encircling hills". Thus both Bradley and Richards suggest that the forms of certain stone circles "echo the characteristic features" of their topographic setting and so provide a "metaphor" for the wider landscape (Bradley 1998, p.122–3). Indeed, Richards goes so far as to suggest that by creating a "a microcosm of landscape" stone circles provided the "physical and cultural centers of the world" for the people who used them (Richards 1996, p.203).

The specific cases cited by Bradley and Richards may well support their argument that stone circles in some sense recapitulate their landscape setting, but it is not clear how far one can generalise this insight, even within one region. As already noted, there is substantial variability in the form and size of stone circles and it may or may not be coincidental that three of the four stone circles cited by Bradley and Richards are among the very largest in Britain (Avebury, Long Meg and Her Daughters and The Ring of Brodgar). In addition, there is the question of intentionality: one can envisage situations where the nature of the terrain is such that it would have been difficult to locate a stone circle so that it did not appear to be enclosed by encircling hills. Of course, this would not prove that the builders of stone circles were not attentive to the visual properties of the circle's setting, but identifying cases where stone circles were built in locations with settings that were not characteristic of the local norm would certainly strengthen the argument. In the remainder of this paper we demonstrate how it is possible to harness the power of contemporary desktop computers to investigate the generality of claims about the visual settings of stone circles and the extent to which they may have been deliberately selected.

3 A GIS-based methodology

Our method for investigating patterning in the visual settings of stone circles has three components: a quantitative measure of the visual properties of landscape setting; a statistically robust inferential framework; and a means of making the first two components computationally tractable. We outline each in turn.

Measures of setting The particular quality of a visual setting which interests us here is one which an observer placed at a specified viewpoint (in this case one located within a stone circle) obtains what Bradley termed a “circular perception of space” (Bradley 1998, p.122), in other words the sense of being located within a topographic basin (Richards 1996). We measure several factors that contribute to this experience:-

Viewshed size The size of the area visible from a specified viewpoint (the viewshed) does not directly measure the circular perception of space since viewsheds of equal size can be very different in shape. Nevertheless, viewshed size may provide a rough first proxy for the ‘basinlike’ feel of a setting to the extent that the notion of a basin presupposes a bounded area and thus a less than maximal viewshed size.

Fragmentation More subtly, we understand the notion of a ‘basin’ to imply not just a rim, in this case a clearly defined far horizon, but also reasonably uninterrupted visibility within it, in other words, a continuous rather than fragmented viewshed. Even if we can not exactly calibrate the amount of fragmentation required to disrupt the ‘basinlike’ feel of a setting, with a suitable measure we can at least compare the setting of stone circles in this respect. We have devised a measure of viewshed fragmentation based on the ratio of the visible area of a given stone circle’s viewshed to that of a hypothetical viewshed with the same perimeter but which filled a perfect circle. The measure of fragmentation F for a given stone circle c, is calculated as:

$$F = V_c/V_h \tag{1}$$

where V_c is the area of the stone circle’s actual viewshed and V_h is the area of the hypothetical circular viewshed of equivalent perimeter. V_h is calculated thus:

$$V_h = \pi(\frac{P_c}{2\pi})^2 \tag{2}$$

where P_c is the perimeter of the stone circle’s actual viewshed.

Given that for same perimeter, any shape will have a smaller area than that of a circle, the measure of fragmentation, F, will range from $F = 1$ for a perfectly circular unfragmented viewshed to $F \rightarrow 0$ for an irregular and fragmented viewshed.

Properties of the horizon We have already seen how Bradley and Richards both place great emphasis on the horizon—the rim of the basin—in their discussion of the circular perception of space. Lake and Woodman (2003)) explored how the properties of the horizon contribute to the circular perception of space from a viewpoint. They noted that while the far horizon may be perceived as circular, no aspect of the topography need actually demonstrate patterning on a fixed radius (see figure 1 for the very irregular and fragmented viewshed of Long Meg and Her Daughters). In particular, the inclination (vertical angle of view) at which the horizon is seen is a function of both: a) the horizontal distance to the horizon and b) the difference in elevation between the land on the horizon and the viewpoint. Consequently, a viewshed of reasonably constant radius need not offer a constant line of horizon (inclination) if the land on the horizon is very variable in elevation. Conversely, a viewshed of variable radius could in fact offer a constant line of horizon if elevation of land on the horizon happened to vary in the right way. In their study of Scottish recumbant stone circles, Lake and Woodman (2003) demonstrated that this effect is not simply hypothetical, so we follow them in rejecting measures dependent upon specification of a fixed radius (such as concavity—see Yokoyama et al. 2002) and instead adopt their technique of computing the distance to, elevation of and inclination of land on the far horizon at aziumuths from 1 degree through to 360 degrees. For the purposes of statistical testing, we summarise the properties of the horizon of each stone circle in terms of the minimum, maximum, mean, and standard deviation of each of the three attributes just mentioned.

Inferential framework Having outlined how we attempt to measure Bradley's "circular perception of space" in a quantitative framework, we now turn to the issue of how we hope to learn from those measurements. It is important to emphasise that we do not suppose that the our quantitative measures can replicate the experience of actually standing in a stone circle, so to that extent we acknowledge that they do not overcome the well-rehearsed criticism that GIS-based analysis fails to capture the subtlety of real world visibility (see Wheatley and Gillings 2000 for an overview—although the measurement of fragmentation and the inclination of the horizon go somewhat further in this direction than most other published studies. Rather, given that it has been demonstrated that such measures do broadly correlate with variability experienced in the field (Lake and Woodman 2003, pp.701–3), we focus on one of the strengths of a GIS-based approach, which is to provide a large-scale comparative framework within which regional or other patterning might be observed. As already noted, our aim here is to test the generality of claims about the visual settings of stone circles and the extent to which it is possible to support the argument that the settings were intentionally selected for their topographic properties.

Generality We address the question of generality by computing the viewshed size, fragmentation and horizon properties of 529 stone circles distributed across Great Britain. The spatial coordinates were taken from a keyhole markup language (KML) file available for download from the website of *The Modern Antiquarian* (`http://www.themodernantiquarian.com/`), having first rejected sites whose status as a stone circle is uncertain, or where we doubted the accuracy of the coordinates in the light of comparison with other sources (primarily PastScape and CANMORE, the national monuments records of England and Wales, and Scotland, respectively) and inspection in the Google Earth viewer. Barnatt (1989) assembled a gazetteer of British stone circles which records a number of their attributes including his own taxonomic grouping, the maximum diameter of the circle and the likely original number of stones. We were able to cross-reference 306 of the stone circles listed in Barnatt's gazateer with those which we deemed to have credible coordinates in *The Modern Antiquarian* data set (Barnatt provided only low precision coordinates for a significant number of entries in his gazetteer). In the long run it would clearly be desirable to build a definitive spatial data base of British stone circles, but for present purposes even the smaller subset of 306 stone circles for which we have both high precision spatial coordinates and attribute data does at least provide numerous cases in all areas of Great Britain where stone circles are present (predominantly the West and North).

Intentionality We adopt the standard approach from classical inferential statistics, which is to establish the probability that the relevant properties of the topographic setting of each stone circle could be obtained by a random draw from the background population of possible settings, that is to say, if the stone circles had been located without reference to those properties. In archaeological GIS-based analysis this approach was pioneered by Kvamme

(1985; 1988; 1990) and the inferential logic has been thoroughly discussed by Fisher et al. (1997), Lake and Woodman (2000) and Woodman (2000), with further examples of its application in a number of studies including Wheatley's well known investigation of intervisibility between southern British Neolithic long barrows (1995; 1996). There are three points worth elaborating here:-

The first point is simply to remind the reader that this technique can not ultimately disprove that the builders of a stone circle intentionally chose its location for the nature of its viewshed, but what it can do is to increase or decrease our confidence that this was the case according to whether or not we can reliably reject the null hypothesis of a random draw.

Second, in line with much of the work just cited, we use Monte Carlo simulation to compute the significance level at which we can reject the null hypothesis. Specifically, we compute the relevant measures (viewshed size, fragmentation and the summary horizon properties listed earlier) for 55 control sample locations around each stone circle and then compute the (one-tailed) significance level at which we can reject the null hypothesis, p, as $p = R_c/N$, where R_c is the rank of the measure obtained for the stone circle in question among the N control sample locations (see Fisher et al. 1997 and Robert and Casella 2004 for more detail). Figure 2 provides some examples of the results of this process.

The third point to note is the importance of distinguishing mere patterning from causation. Both Fisher et al. 1997 and Woodman 2000 provide useful discussion of this problem, which in this case, is how to be reasonably confident that a viewshed property for which one can reject the null hypothesis of random location was in fact the subject of conscious choice rather than the inadvertent consequence of the choice of some other locational attribute with which it happens to correlate. We attempt to limit the likelihood of such confounding variables by restricting the control sample for each stone circle to points within 500m of that site. In this way, we accept that there may have been myriad other reasons for the rough location of stone circles (such as placement within a territory, proximity to or distance from settlement, etc.) and concentrate on testing whether there is statistical support for the hypothesis that, within these constraints, people sought out locations which afforded particular visual properties. This method also has the further benefit over global control sample of being less likely to produce spurious significance owing to the fact that, for example, no stone circles (setting aside the timber Holme I and Holme II) are found in the flat lands of northern East Anglia.

Computational tractability The GIS-based methodology just outlined required the computation of the viewsheds of each stone circle, plus the points in the control samples, followed by post-processing of the computed viewsheds to extract the horizons and subsequently compute the fragmentation and horizon measures. The viewsheds were computed using the British Ordnance Survey's Land-Form Panorama digital terrain model, which describes the terrestrial elevation of Great Britain on a 50m grid.

All computation was carried out using GRASS GIS software (GRASS Development Team 2012) running under Linux. We used the `r.horizon` GRASS module written by Lake (see Lake and Woodman 2003, p.697 for details) to extract the viewshed horizons from previously computed viewshed maps, and then Unix bash shell and R statistical programming language (R Development Core Team 2012) scripts written by Ortega to compute the fragmentation and other summary statistics from the horizon maps. Since post-processing the viewshed contributed only a small fraction of the total processing time we focus here on describing the method which allowed us compute the viewsheds of the stone circles and their associated control points.

The challenge we faced was to compute some $529 \times 56 = 29624$ viewsheds, each potentially extending in excess of 100km from the viewpoint and covering some 12.5 million raster map cells. Our solution to this challenge was to embed an efficient viewshed module in a shell script which effected adaptive parameterisation. The shell script ultimately invokes the `r.viewshed` GRASS module to compute the viewshed of each stone circle / control point: this module utilises a fast algorithm written by Laura Toma and colleagues (Fishman et al. 2009). Before doing so, however, the script limits analysis to the smallest possible geographical region consistent with the need to compute a far horizon truncated only by the curvature of the earth or intervening land, but not by an arbitrary maximum viewing distance. This is achieved in 3 steps:-

1. The maximum possible distance to the horizon D for a viewpoint in Great Britain was

calculated using the formula $D = \sqrt{2Rh}$ (Lodge and Muirhead 1924) where R is the average radius of the earth (6371009m) and h is the maximum possible height differential between a viewpoint and another location that might be visible from it.

2. For each stone circle / control point D is used to calculate the boundary of a geographical region marking the maximum extent of visibility around that stone circle as if it happened to have a viewshed with the maximum distance to the horizon that is possible anywhere in Great Britain. Since that is unlikely, this region is searched for the maximum height differential with the stone circle in question and that value is then used to calculate a further reduced geographical region as per step 1.

3. For each stone circle / control point the second smaller geographical region is used to constrain the area which much be examined when computing the viewshed. This has two advantages: first it ensures that r.viewshed need only sweep the minimum collection of raster map cells necessary to locate the true maximum extent of the viewshed; and second it ensures that the minimum necessary amount of data is loaded into computer memory, thereby reducing the likelihood of needing to use swap-space on disk, which is of course orders of magnitude slower than accessing physical memory (for example, we found that r.viewshed was nearly four times slower when arbitrarily limited to 512Mb of physical memory than when it was configured so as to load the entire geographical region into physical memory).

This technique allowed us to compute the necessary 29624 viewsheds in approximately 425 hours (18 days) using an Intel Core i5-2500 based desktop computer offering 4 cores and 4 logical processors each running at 3.3 GHz (Note that GRASS GIS software is not currently thread-safe, so we launched parallel processes to benefit from the availability of multiple processors).

4 Statistical analysis

Armed with 29624 viewsheds we have undertaken a variety of statistical analyses of their size and fragmentation, as well as the distance to, elevation of and inclination of the locations falling on their horizons. In keeping with the inferential framework describe above, we use spatial plots, scatterplots, boxplots and cluster analyses to explore patterning in viewshed properties, and Monte Carlo simulation to address the issue of intentionality. There is insufficient space here to reproduce every graphical output from our analyses, but we do attempt to illustrate the principal findings, measure by measure.

Viewshed size (area) The viewsheds of our larger sample of 529 stone circles range in area from $21011.25km^2$ to $0.98km^2$. The numerical distribution is strongly skewed towards smaller sizes, such that the median ($137.06km^2$) is substantially smaller than the mean ($1599.92km^2$) and only 23% of stone circles have viewsheds that exceed the mean. Viewshed area does not exhibit a convincing linear or low-order polynomial correlation with the elevation of the corresponding stone circle, although it is the case that the largest viewsheds occur at lower elevations (only 7 of the 55 stone circles with viewsheds in excess of $5000km^2$ are located at elevations above 300m. This result interesting as it is commonly supposed that higher viewpoints have large viewsheds. There is similarly no easily modelled relationship between viewshed area and either slope or aspect, although the stone circles with the very largest viewsheds are most often located on slight slopes and land facing south through west to north. Among the 306 stone circles for which we have attribute data there is no simply modelled relationship between viewshed area and the maximum diameter of the circle, although the largest circles (with diameters in excess of 60m) all have small viewsheds (all below the mean viewshed area and all except 2 below the median).

There is very pronounced geographical patterning in the spatial distribution of viewshed area (figure 3). In particular, the central Scottish stone circles have small viewsheds, the west Cumbrian and most Pennine stone circles have moderate sized viewsheds, and the south western stone circles (Devon and Cornwall) have large viewsheds. Among the Scottish recumbant stone circles (Grampian) there is a clearly defined gradation from small viewsheds in the west to large viewsheds in the east. In general (the central Pennines excepted), stone circles with larger viewsheds are located in closer proximity to the sea.

Monte Carlo simulation allows us to address the question of whether the observed numerical and/or spatial distributions of viewshed area imply intentional choices by those who built stone circles. The results indicate that 25.8% of the smaller sample of 306 stone circles have viewsheds which are smaller or larger than would be expected by chance alone ($p = 0.05$), and this increases to 39.2% at a more relaxed significance level of $p = 0.1$. This does not outwardly appear very promising, but there is an interesting relationship between whether viewshed sizes are significantly different from those expected by chance alone and their absolute size. Specifically, figure 4 demonstrates that most of the very largest viewsheds are smaller than expected and that none of the very large viewsheds are larger than expected. Furthermore, the median of viewshed sizes which are smaller than expected is greater than the median of those which are not statistically distinguishable from the background population. We will return to what this might mean in our concluding comments. Turning to the spatial distribution of viewshed sizes, there is no evidence of robust spatial patterning in whether viewshed sizes are smaller or larger than expected. Thus, while it may not be true of any particular stone circle, the general tendency for larger viewsheds to occur in closer proximity to the sea is one that would be expected without the exercise of intentional choice.

Viewshed fragmentation The viewshed fragmentation of our larger sample of 529 stone circles ranges from 0.502 to 0.0000766. The numerical distribution is massively skewed towards smaller sizes, such that the median (0.00476) is substantially smaller than the mean (0.0146) and only 22% of stone circles have viewsheds that exceed the mean. Given that the fragmentation statistic, F, ranges from $F \rightarrow 0$ for very high fragmentation to $F = 1$ for a perfectly circular and continuous viewshed it is clear that the vast majority of stone circles have very fragmentary viewsheds, something which is born out by examination of viewshed maps. Viewshed fragmentation does not exhibit a convincing linear or low-order polynomial correlation with the elevation, slope or aspect of the corresponding stone circle. That said, 12 of the 15 stone circles with the least fragmented viewsheds (i.e. $F > 0.1$) are located below 200m above sea level, and 13 of them on slopes of less than 5 degrees. Among the 306 stone circles for which we have attribute data there is no simply modelled relationship between fragmentation and the maximum diameter of the circle. The largest circles (with diameters in excess of 60m) all have very fragmented viewsheds ($F < 0.0180$), although the distribution of fragmentation values is so massively skewed that this is also true of 82% of all stone circles for which we have attribute data. However, considered another way, 90% of stone circles whose viewsheds are less fragmented than the mean are 30m or less in diameter.

There is some geographical patterning in the spatial distribution of viewshed fragmentation (figure 5). Most notably, stone circles nearer the sea are more likely to have less fragmented viewsheds, as might be expected if those viewsheds include a significant area of sea. Inland circles have more highly fragmented viewsheds. This geographical cline from low to high fragmentation is especially clear as one moves from east to west through the Scottish recumbant stone circles.

The results of the Monte Carlo simulations indicate that 22.6% of the smaller sample of 306 stone circles have viewsheds which are more or less fragmented than would be expected by chance alone ($p = 0.05$), and this increases to 36.6% at a more relaxed signficance level of $p = 0.1$. Unlike with viewshed size, there is no discernible pattern in either the numerical or geographical distribution of statistically significant cases. It is worth noting, however, that viewsheds are three times more likely to be significantly ($p = 0.05$) less fragmented than expected by chance than they are to be more fragmented than expected.

Horizon properties As discussed above, we follow Lake and Woodman 2003 in computing for each stone circle the distance to, elevation of and inclination of land on the far horizon at aziumuths from 1 degree through to 360 degrees. However, whereas Lake and Woodman studied 19 stone circles, we are dealing with a maximum of 529 sites plus a further 29095 control points and for this reason do not analyse the horizon measures by azimuth, but instead summarise them in terms of the minimum, maximum, mean and standard deviation per stone circle / control point. We discuss distance, elevation and inclination in turn, but before doing so it is worth noting that these measures show very little correlation with one another per stone circle / control point: this is unsurprising given that multiple combinations of distance and elevation can produce the same inclination. With just one exception, we also find no convincing correlation between any of the three horizon measures and the elevation, slope or aspect of the stone circle itself. The exception is a strong positive linear relationship between the minimum elevation of the horizon and the elevation of the stone circle: again, this is as expected.

Elevation of the horizon The elevation of the horizon is variable both within and between stone circles, as can be seen from the summary statistics presented in table 1. In this table, the columns refer to per-circle summaries, while the actual numerical values presented in rows measure the variability in per-circle summaries across all 529 stone circles.

While the minimum horizon elevation at any given stone circle varies from zero to 555m, figure 6 shows that the minimum at any stone circle with a large viewshed (in terms of area) is always zero, confirming that large viewsheds include the sea. The maximum horizon elevation does not correlate with viewshed size. Figure 6 also shows that high mean horizon elevation is, as one might expect, associated with small viewsheds. There is no correlation between horizon elevation and the maximum diameter of stone circles.

The Monte Carlo simulations suggest that between 19% and 25% of the 306 stone circles for which we have attribute data have horizon elevations characterised by summary statistics which are different from those expected by chance alone (at $p = 0.05$). In these cases the minimum horizon elevation is equally likely to be lower or higher than expected by chance, but the maximum, mean and standard deviation of horizon elevation are variously 2–3 times more likely to lower than would be expected by chance. Interestingly, figure 7 shows that when the maximum and mean horizon elevation are greater than expected they are also low in absolute terms, and the converse is also true. We return to the possible significance of this in our concluding comments.

Distance to the horizon The variability in distance to the horizon is documented in table 2, which laid out in the same way as table 1. The minimum distance to the horizon at any given stone circle does not correlate with viewshed area, but there is a clear relationship between both mean and maximum distance to the horizon and viewshed size. Although viewsheds with large mean and maximum distance to the horizon can be small in terms of their area (because they are highly fragmented), increasingly large viewsheds are, as one might expect, associated with larger mean and maximum distances to the horizon (figure 8). There is no correlation between distance to the horizon and the maximum diameter of stone circles.

The Monte Carlo simulations suggest that the per-circle maximum, mean and standard deviation of distance to the horizon are smaller or larger than would be expected by chance ($p = 0.05$) at 44%, 38% and 39% of stone circles (the sample of 306) respectively. Interestingly, in these cases the measures are 5.8–6.5 times more likely to be smaller than expected by chance than they are to be larger than expected. Furthermore, figure 9 shows that the values of smaller than expected measures of distance to the horizon are typically high in absolute terms.

The latter finding also shows spatial patterning. A majority of the eastern Scottish recumbant stone circles have viewsheds with a smaller than expected maximum distance to the horizon, whereas this is not so at the more westerly recumbant stone circles. Approximately 40%-50% of south western and Welsh stone circles also have viewsheds with a smaller than expected maximum distance to the horizon. In our concluding comments we discuss how this finding relates to the tendency for these same viewsheds to be large.

Inclination of the horizon Table 3 documents the variability in the inclination of the horizon and is laid out in the same way as table 1. The distribution of the minimum horizon inclination across the sample of 529 stone circles is approximately normal, centred around a line-of-sight to the horizon that is close to horizontal. In general, stone circles at which the minimum inclination falls more than 0.5 degree either side of horizontal have small viewsheds (figure 10). The 84% of stone circles at which the minimum inclination falls with this band have viewsheds ranging from very small to very large. The association of large viewsheds with near horizontal minimum inclination is an expected outcome of them also having distant horizons, as is their association with low standard deviation of inclination. There is a similar relationship between mean horizon inclination and viewshed size, except that in this case 92% of stone circles have a mean line of site to the horizon which is horizontal or above. The relationship between large viewsheds and mean minimum inclination, low mean inclination and low standard deviation of inclination is largely repeated for the maximum diameter of stone circles (figure 11), at least in the 306 cases for which we have that information. That said, the 5 very largest stone circles in our sample (Avebury, Long Meg and Her Daughters, Stanton Drew Central, The Ring of Brodgar, The Twelve Apostles) actually have viewshed horizons with mean inclinations in the range 90.70–91.34 degrees, making their horizons appear on average higher than at 53% of stone circles in the sample, although in none of these 5 cases is the horizon inclination higher than expected (at $p = 0.05$ or $p = 0.1$). We return to this point in our concluding comments.

The Monte Carlo simulations suggest that only 9% and 6% of stone circles have horizons characterised by a minimum or maximum inclination, respectively, that is either smaller or larger than would be expected by chance alone (at $p = 0.05$). It is notable, however, that where significantly different from the control sample, the maximum horizon inclination is over five times more likely to be higher rather than lower than expected. This might be taken as tentative evidence for the intentional choice of locations with horizons providing a pronounced 'rim', especially as only 7% of these stone circles have a smaller than expected mean horizon inclination. This inference does not, however, fit so well with the fact that slightly more (by a factor of 1.8) stone circles have horizons characterised by a mean inclination which is lower rather than higher than expected, but in this case it may be their builders were first and foremost seeking a reasonably constant line of horizon, since only 7% of these stone circles have greater than expected variability in horizon inclination (standard deviation) whereas 44% have lower than expected variability.

5 Conclusion

We computed the viewsheds of some 529 stone circles (approximately 60% of known circles) to explore the generality of Bradley and Richards' suggestions that these prehistoric monuments were built in locations that offered a "circular perception of space" (Bradley 1998, p.122–3). We also used Monte Carlo simulation in an attempt to find statistical evidence for intentional placement of stone circles in settings with particular visual properties. Our principal findings are as follows:-

Geographical distribution of viewshed properties The stone circles with the largest viewsheds are found in south west England, western Cumbria and among the more easterly of the Scottish recumbent stone circles. The stone circles with the smallest viewsheds are generally found in central southern England, the southern half of Wales, the eastern Scottish border counties, central Scotland and among the more westerly Scottish recumbent stone circles. The Monte Carlo simulations provide no evidence that this global variability in viewshed size reflects anything other than broad differences in local terrain form and, in particular, the likelihood of at least part of the viewshed including the sea. The impact of the latter is also seen in the more coastal distribution of the least fragmented viewsheds.

Although there is no evidence that regional variability in the size and fragmentation of viewsheds is the result of different choices by the builders of stone circles, that does not alter the fact that those building and using them in different parts of Great Britain may have experienced them differently in terms of their relationship with their topographic setting. This is particularly striking in the case of the west–east geographical cline in the size and fragmentation of the viewshed of the Scottish recumbent stone circles, particularly given that they were presumably built and used by related groups with similar cultural values. Does this mean that viewshed size and fragmentation was largely irrelevant to these people, at least relative to, say, lunar orientation (Ruggles 1999; Bradley et al. 2005).

Intentional selection of basin-like settings One might intuitively suppose that a perfectly basin-like setting would have a relatively unfragmented small or moderately sized viewshed. The Monte Carlo simulation analyses of viewshed area and fragmentation provide evidence that the builders of at least some (22% at $p = 0.05$) stone circles may have sought topographic settings which offered smaller viewsheds than those typical of the locality. The importance of restricting the viewshed in some way is supported by the finding that most of the very largest viewsheds are actually smaller than those typical of other viewpoints in the locality and, crucially, there is no evidence for the choice of larger than typical viewsheds. A similar result was obtained for viewshed fragmentation: stone circle viewsheds with atypical fragmentation are three times more likely to be less rather than more fragmented than is typical of other viewpoints in the locality.

Interesting though these results are, viewshed area and fragmentation may not be reliable indicators of Bradley's "perception of circularity". One of his examples of this phenomenon, Long Meg and Her Daughters, has a viewshed that is small only because it is also highly fragmented. The viewshed from Long Meg and Her Daughters does, however, have relatively high mean horizon inclination and low standard deviation of inclination, supporting Lake and Woodman's (2003) claim that the properties of the horizon (especially the inclination) are likely to provide a more direct measure of the impression of circularity. The Monte Carlo simulation analysis of horizon elevation was inconclusive with respect to whether the builders of stone circles sought locations with particularly high or low horizon elevations. That said, for the 24% of stone circles where there is evidence for locally atypical horizon elevation, one might tentatively offer evidence for the operation of some kind of norm in the fact that their builders seem to have chosen locations with atypically high horizon elevations when these were low in absolute terms and, conversely, chosen locations with atypically low horizon elevations when these were high in absolute terms. Some 38% of stone circles have viewsheds with a smaller or larger mean distance to the horizon than is typical of other viewpoints in the locality and these are around six times more likely to be smaller than larger, again pointing to a desire to 'contain' the viewshed. Finally, as discussed in the results above, the Monte Carlo simulation analysis of horizon inclination provides tentative support that the builders of at least some stone circles sought to minimise the variability in the line of the horizon (its inclination). Overall then, our analysis provides some evidence that the desire for a contained and possibly basin-like viewshed may have been a factor in the siting of up 25% of the stone circles in our sample.

Large stone circles As discussed in the results, it is notable that the largest stone circles in our sample (i.e. those in excess of 60m maximum diameter) have relatively small viewsheds (in terms of area) which are highly fragmented. That said, those viewsheds are also characterised by moderately high mean horizon inclination and low variability in the horizon inclination. This suggests that the viewsheds of these very large stone circles combine two properties: on the one hand they may offer a "circular perception of space" (Long Meg and Her Daughters and The Ring of Brodgar are both cited by Bradley and/or Richards in this regard), but on the other hand their highly fragmented viewsheds provide ample scope for the control of the visual encounter of these sites, along the lines suggested by Barrett (1994) and Thomas (1993) for Avebury. Despite this tantalising prospect, the Monte Carlo simulation analyses provide no evidence that any of these very large stone circles were intentionally built in locations offering these particular properties, although it may be that in these cases the control points should have been drawn from a wider area, on the grounds that larger monuments were built and/or used by larger groups of people spread over a larger area.

In light of these results—tentative though they are—we hope this paper demonstrates that carefully designed experimental methods in combination with contemporary desktop computing power now make it possible to deploy GIS-based viewshed analysis in a manner which appeals to its strengths rather than weaknesses, that is, the comparative analysis of large numbers of sites at a regional or larger scale.

Tables

	Min. elevation	Mean elevation	Max. elevation	Std. dev.
Min.	0.0	1	136	11.4
Max.	555	822	1309	406.6
Mean	110.4	350.0	766.6	158.3
Std. dev	118.7	175.7	282.4	82.3

Table 1. Elevation of the horizon (metres).

	Min. distance	Mean distance	Max. distance	Std. dev. distance
Min.	0.05	1.34	2.45	0.54
Max.	6.76	124.75	129.88	21.58
Mean	0.32	41.36	72.95	61.53
Std. dev	0.50	30.73	38.95	14.10

Table 2. Distance to the horzion (kilometres).

	Min. inclination	Mean inclination	Max. inclination	Std. dev. inclination
Min.	84.55	89.76	90.70	0.11
Max.	94.78	99.49	118.00	5.61
Median	89.94	90.70	95.00	0.72
Mean	89.97	91.07	96.26	0.99
Std. dev	0.65	1.30	4.21	0.81

Table 3. The inclination of the horizon (decimal degrees).

Figures

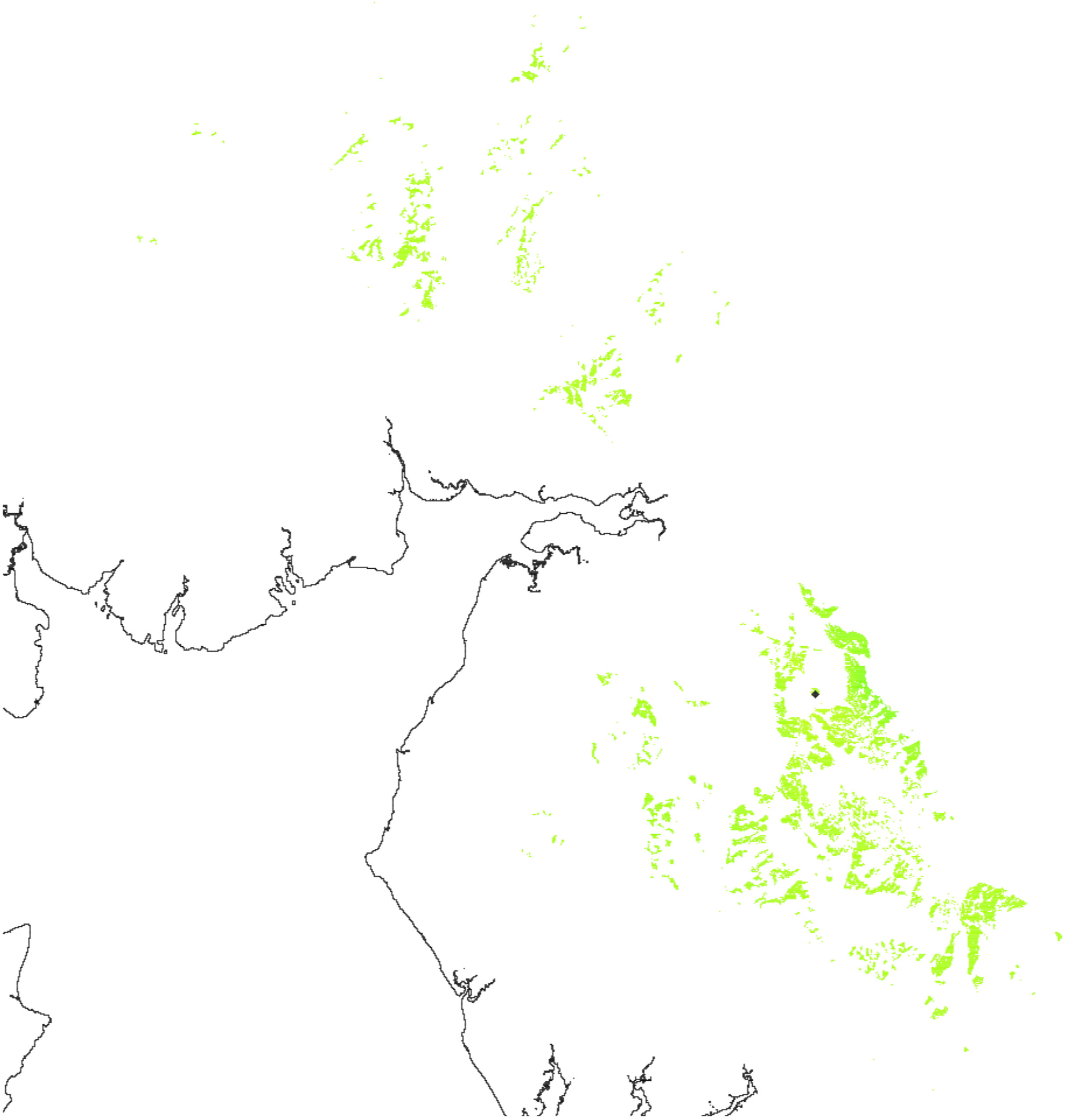

Figure 1. The fragmented viewshed of Long Meg and Her Daughters. (Derived from elevation data ©Crown Copyright Ordnance Survey. An EDINA/JISC supplied service.)

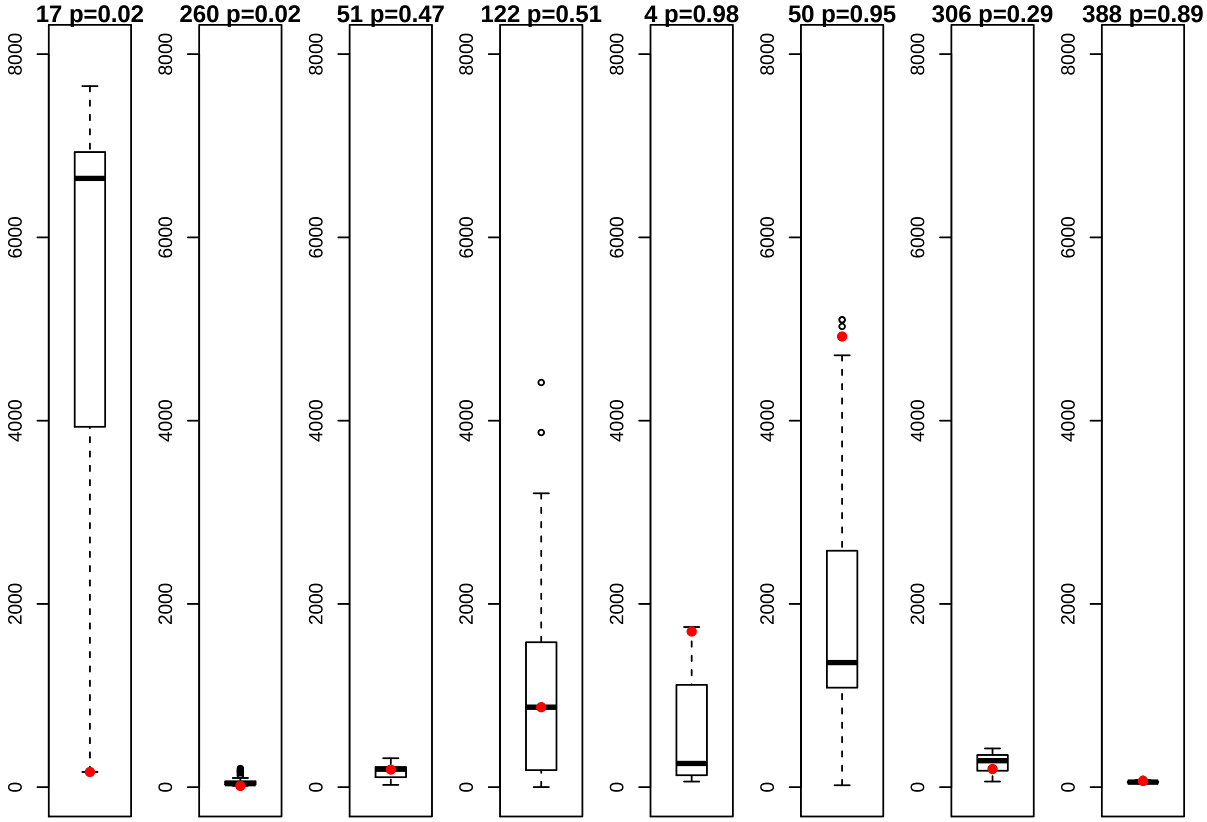

Figure 2. Eight examples from the Monte Carlo simulation of viewshed area. Stone circles 17 and 260 have viewsheds which are smaller than expected of viewpoints in the locality; 51 and 122 have viewsheds which are typical, 4 and 50 have viewsheds which are larger than expected. Stone circles 306 and 388 are Long Meg and Her Daughters, and The Ring of Brodgar, respectively.

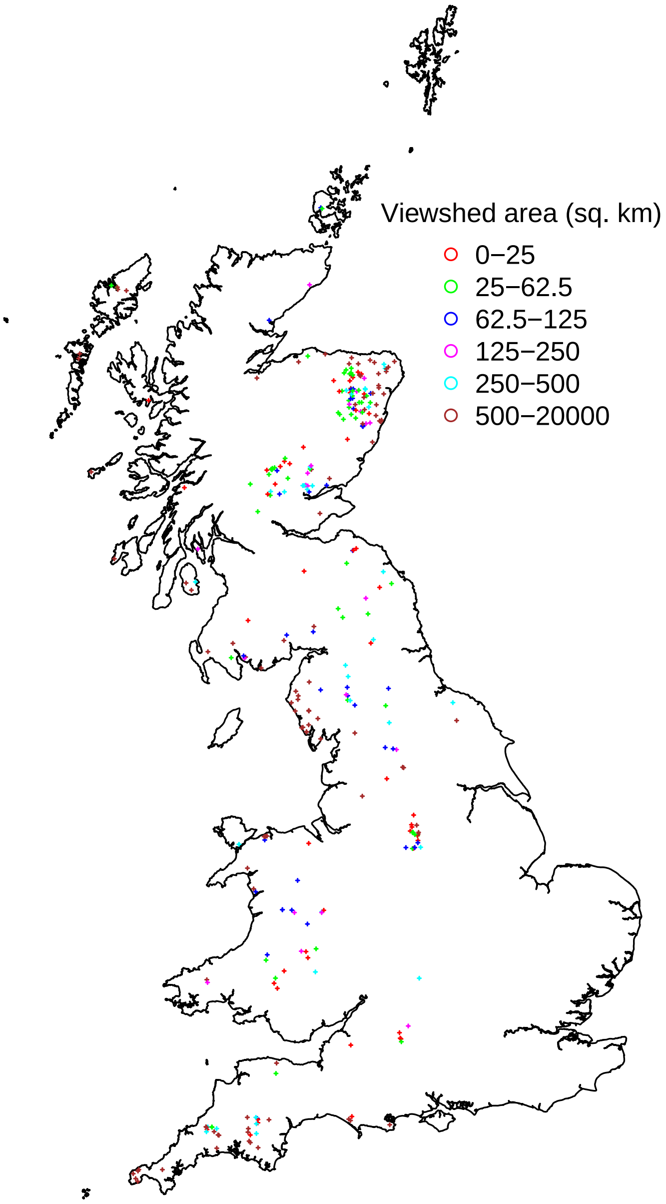

Figure 3. The geographical distribution of the stone circles studied, showing their viewshed area.

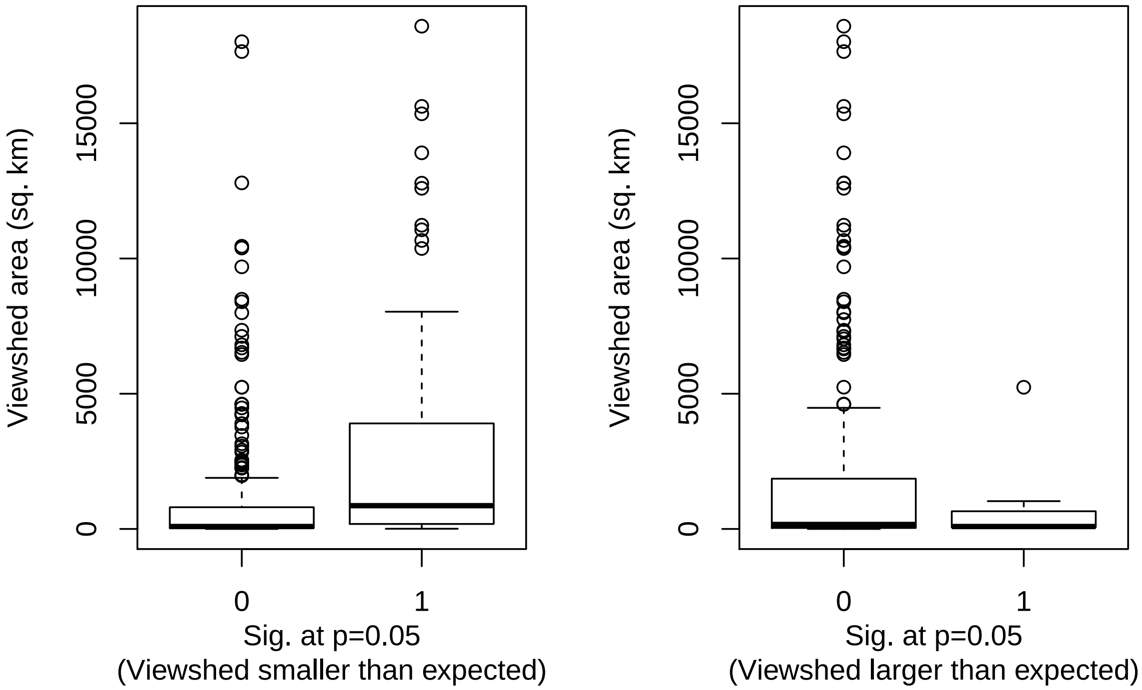

Figure 4. The relationship between the statistical significance of viewshed areas and their absolute values.

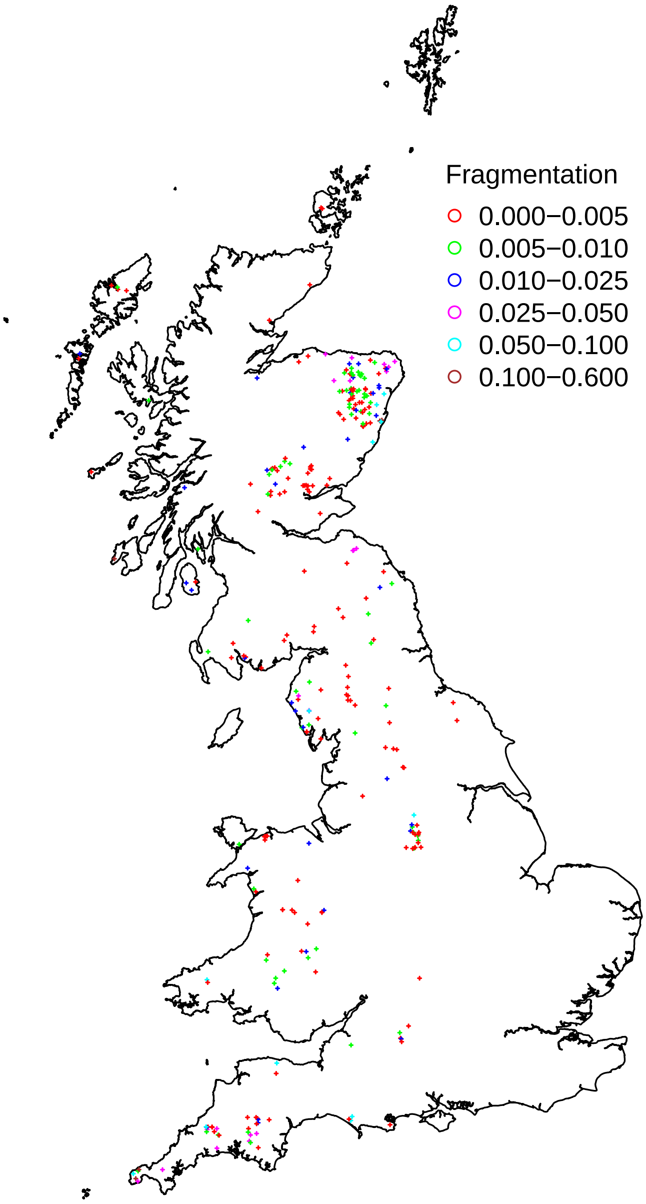

Figure 5. The geographical distribution of the stone circles studied, showing the fragmentation of their viewsheds.

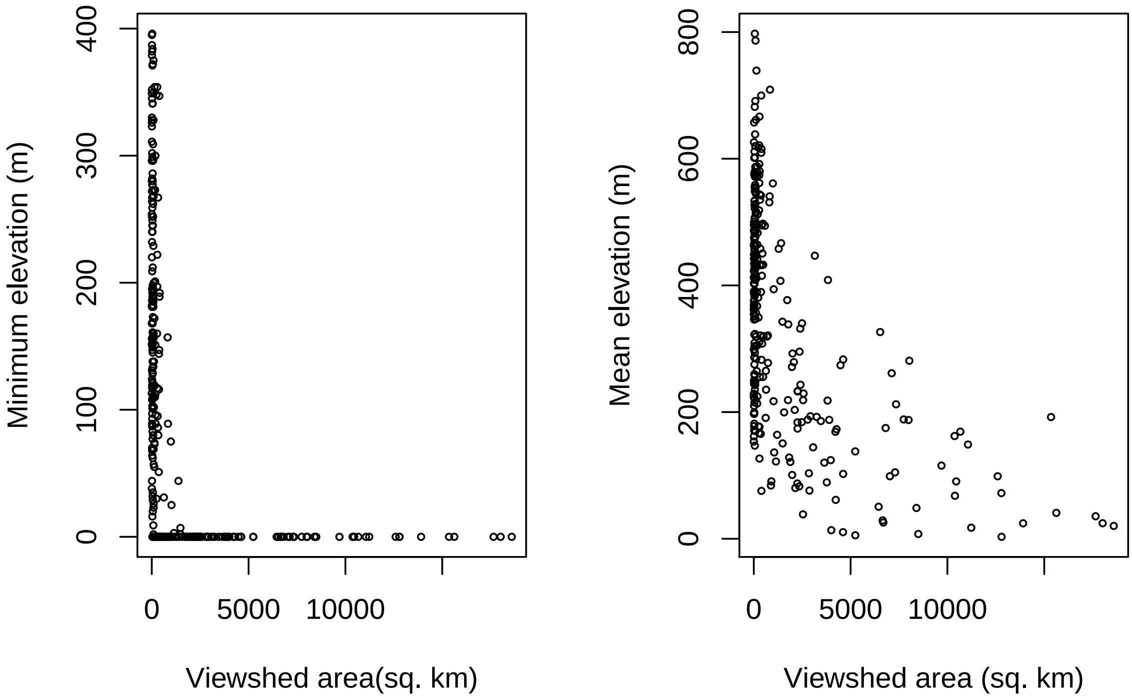

Figure 6. The relationship between the elevation of the horizon and viewshed area (Avebury omitted).

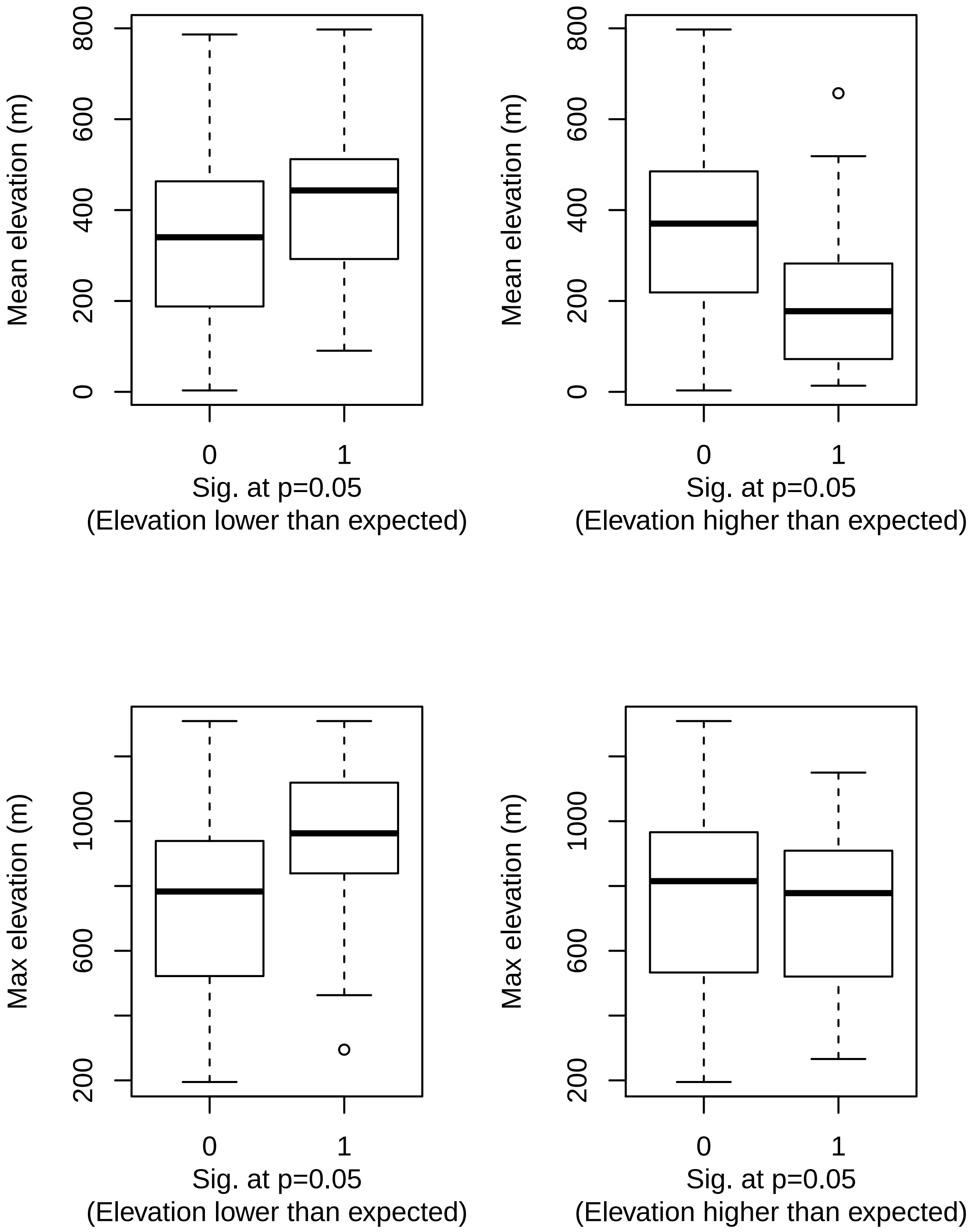

Figure 7. The relationship between the statistical significance of horizon elevation and its absolute value.

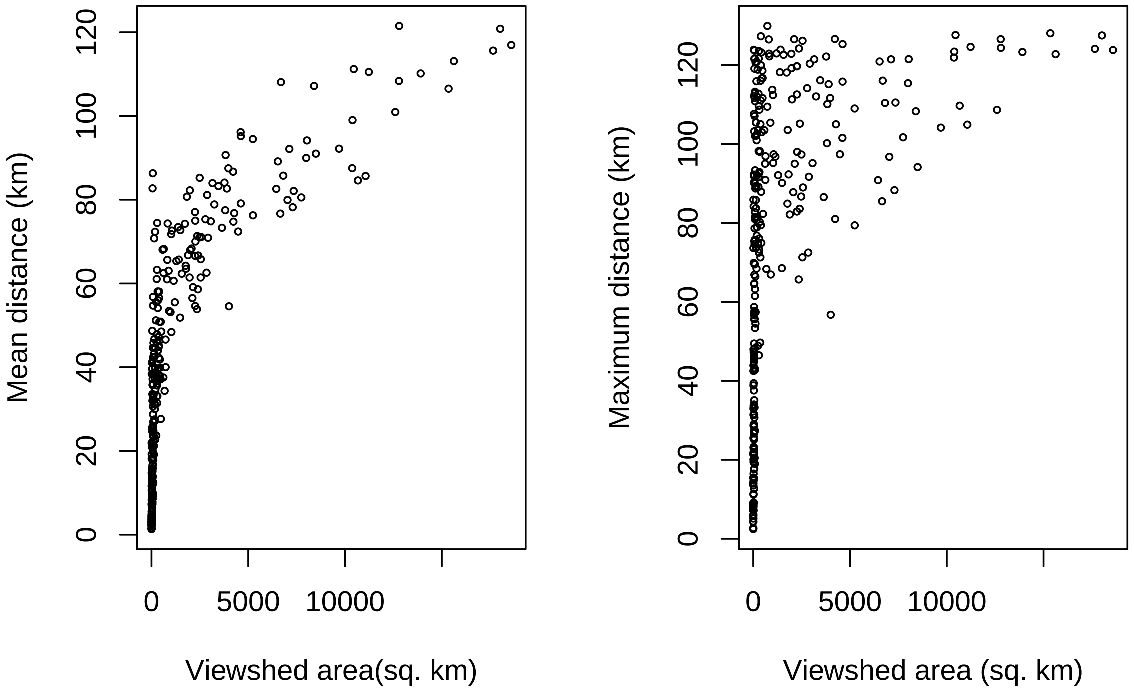

Figure 8. The relationship between the distance to the horizon and viewshed area (Avebury omitted).

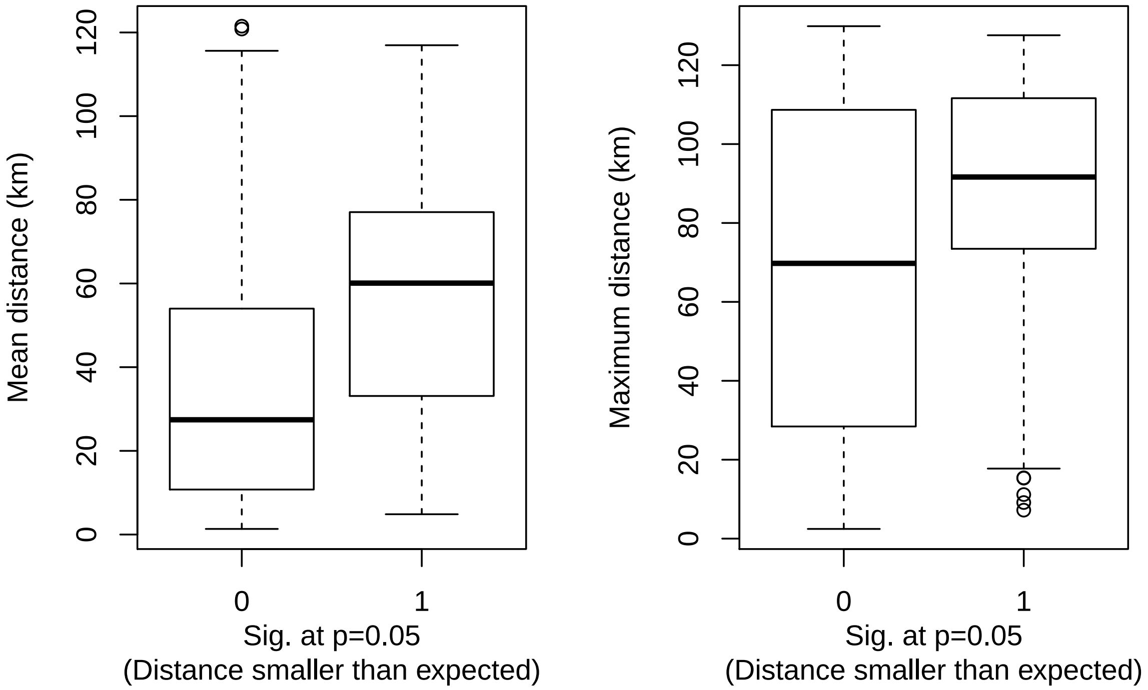

Figure 9. The relationship between the statistical significance of the distance to the horizon and its absolute value (Avebury omitted).

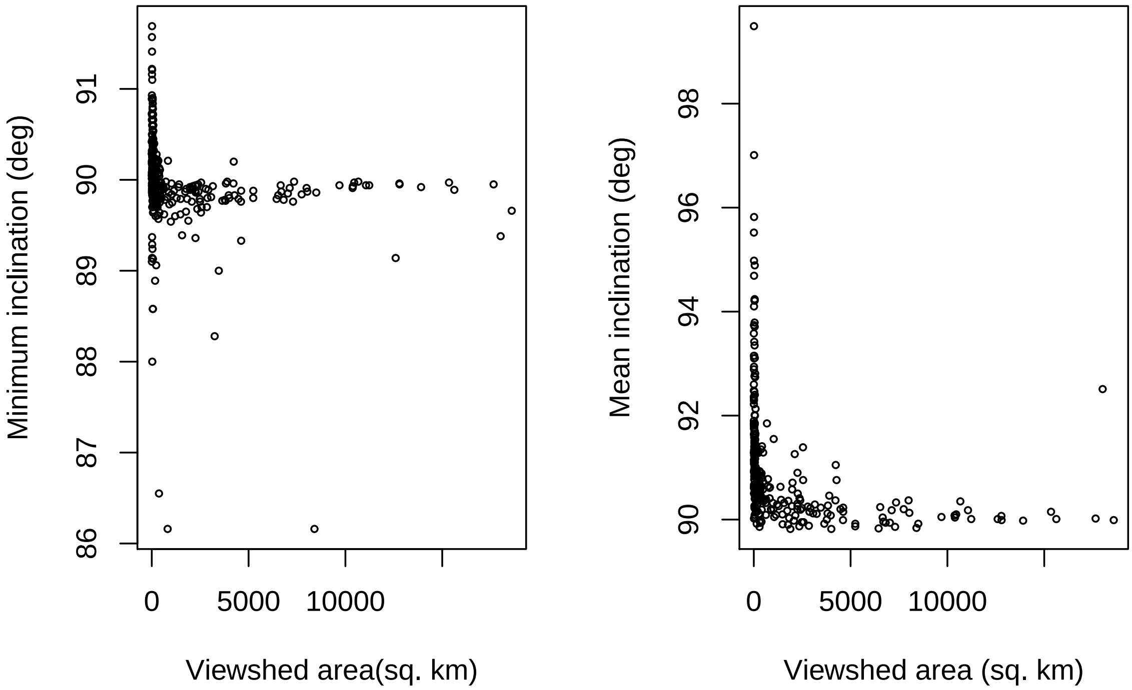

Figure 10. The relationship between the inclination of the horizon and viewshed area (Avebury omitted).

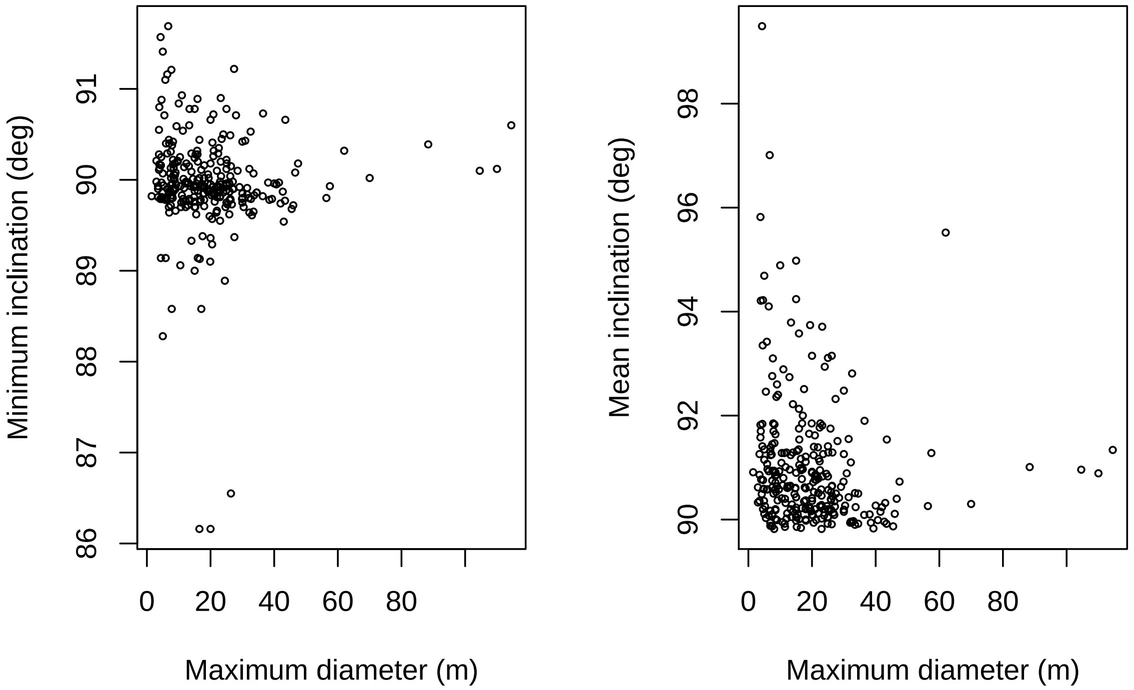

Figure 11. The relationship between the inclination of the horizon and the maximum diameter of the stone circle (Avebury omitted).

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