

# ***Analysing change through time within a cultural landscape: conceptual and functional limitations of a GIS approach***

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## **Introduction: the attraction of GIS.**

The rapid uptake of Geographic Information Systems in archaeology is rooted in the historical importance of maps and plans as basic tools within the discipline. While many other computer-based and quantitative methods remain conceptually remote to the majority of archaeologists, even elementary GIS analysis and especially output in the form of maps is of immediate relevance. The power to visualise the spatial component of archaeological data within the contrasting settings of national and local Cultural Resource Management and at varying scales of analysis from the intra-site to the regional level, has contributed substantially to the current high level of awareness, if not actual usage, of GIS in archaeological circles. It is important to bear in mind, however, the dangers of being seduced by this very attractive technology which has many alluring powers, including the ability to turn the old computer adage of ‘garbage in – garbage out’ into the GIS equivalent of ‘garbage in – pretty maps out’.

This chapter offers some comments on GIS approaches to a fundamental aspect of landscape archaeology: that of visualising and measuring change through time. A landscape is a continually evolving three-dimensional space where one of the dimensions is time. In GIS terms this can be envisioned with sites as objects anchored on the three axes. The representation, and compression, of the temporal axis upon an essentially two-dimensional landscape surface creates a palimpsest which is the data of the landscape archaeologist. As the doyen of British field archaeology, O. G. S. Crawford wrote many years ago:

The surface of England is a palimpsest, a document that has been written on and erased over and over again; and it is the business of the field archaeologist to decipher it.  
(Crawford 1953, p. 51)

Of course, this does not apply only to England, but to many parts of the world where the task of deconstructing a temporally rich and complex landscape and identifying change through time is fundamental to the understanding of past human activity. This paper explores the current

inability of GIS technology to perform this task. It moves on to discuss the next generation of software which promises to be more pertinent to three-dimensional and four-dimensional analysis and proposes a model for change through time, based on a probability quotient of occupation or use, applicable to archaeological landscapes.

## **GIS and landscape archaeology**

### **Background**

There is a burgeoning literature covering the theory, concepts, technology and applications of GIS and the interested reader requiring basic information is pointed towards the following texts: Burrough (1986), Maguire, Goodchild & Rhind (1991) and Star & Estes (1990). Applications in archaeology are given full coverage in Allen, Green & Zubrow (1990) with a useful overview in Kvamme (1989; 1992) and Lock and Harris (In Press) also synthesise and demonstrate the analytical capabilities of GIS which are of interest to archaeologists.

As GIS applications in archaeology begin to mature from their relatively infant origins in the mid-1980s, so trends can be identified which parallel the adoption of the technology in other disciplines (Harris & Lock 1990). The first stage is the overriding concern with the inventorying of large spatial data-sets then moving into analysis as a secondary consideration. The final stage is the development of an integrated management system in which the GIS becomes just one component within an information system with modelling, decision support and analytical capabilities. Very few archaeological applications have advanced this far although work in the Netherlands (Roorda & Weimer 1992) and France (Arroyo-Bishop & Lantarda Zarzosa 1992) are approaching such sophistication. In tandem with the development of GIS based CRM systems focused on extensive inventorying and data management, equal development has been devoted to the advancement of methodology and spatial analysis within small archaeological research units and by individuals.

There is an interesting and important point to be made here concerning the use of GIS in archaeology and its relationship with archaeological theory. Accepting that the adoption of a new technology such as GIS will involve initial stages of use whereby existing practices are repeated and any new potential is not utilised, the important consideration, and one being debated in disciplines other than archaeology (Openshaw 1991), is whether GIS is simply an atheoretical tool or is capable of influencing the development of theory. The challenge facing GIS is whether it represents a change in how archaeologists formulate and solve problems or whether it is merely a new way of doing existing things. Despite GIS applications in archaeology being a fairly recent field it does appear that philosophical and methodological questions are being raised together with purely technological ones. The area of perception within a landscape and cognitive landscapes is an interesting example where the view shed capabilities within GIS are stimulating the

development of new theoretical approaches (Wheatley 1993). The current discussion of representing change through time is directly related to the potential of three-dimensional GIS, Geo Scientific Information Systems – GIS.

Whatever and wherever the GIS application, the aim is to model aspects of real-world spatial phenomena and their spatial relationships. As will be shown later, problems arise when the modelling capabilities of the software are unable to reflect the underlying archaeological theory. This results in the archaeology being forced into a technological straight jacket. One significant example of this lies in the two-dimensional view of the archaeological world enforced by present GIS technology. Current GIS is based on two-dimensional data structures with data elements organised into coverages which can be viewed as two-dimensional maps or as ‘2.5- dimensional’ Digital Terrain Models (DTM), both allowing the draping of other coverages upon them. Spatial analysis is in terms of two-dimensional spatial relationships between data elements either within a single coverage or between coverages where the third axis is not continuous but is limited to a series of coverages. The question to be addressed here is the extent to which these data structures constrain the representation of change through time.

### **Representing time**

The procedure of GIS-based landscape analysis starts with the identification of individual archaeological features from within often complex palimpsests that comprise the archaeological landscape. This involves the consideration of archaeological theory and modelling that classify elements of the cultural landscape according to accepted archaeological schemes. Taking the example of the 500 km<sup>2</sup> around Danebury hill fort in central southern England (Lock & Harris In Press), the individual archaeology is conceptually categorised into acceptable codes such as ‘hill fort’, ‘field system’, ‘settlement’ etc. Each element is assigned spatial boundaries and temporal limits together with its relevant attribute data so that they can be fitted together to create an archaeological model of the real world landscape. Within the constraints of the technology, the resulting digital model is the closest possible replication of the conceptual archaeological model which itself is several steps removed from the real world archaeology. It is important to differentiate between the conceptual model defined by the archaeology and the digital model defined by the technology.

The inadequacy of the GIS model of the ‘real’ archaeology is nowhere more apparent than in temporal analysis. Implicit within the conceptual model is the designation of a time span or period code to each feature which can be simplistically represented within the GIS model in one or a combination of two ways. Temporal coding could be stored as an attribute in the attribute database or coverages could be organised temporally which in archaeological terms usually means coverages represent periods or sub-periods. In the Danebury example, the six coverages are for

the Neolithic, the Early Bronze Age, the Late Bronze Age, the Early Iron Age, the Late Iron Age and the Romano-British period. The fact that GIS technology forces time to be treated as a categorical rather than continuous variable is readily acceptable to archaeologists because of existing limitations of archaeological conceptual models. Many temporal classifications and typologies require that time is broken down into a series of periods, suitably labelled and relatively positioned usually end to end.

This categorical approach to dealing with time is clearly gross oversimplification which influences the study of change through time whereby characteristics of each category are compared and differences deemed to be significant. Even so, this methodology is well established within archaeology and fits conveniently with the coding required for working with both traditional database software and GIS. Archaeologists use labels such as 'early neolithic' and 'late neolithic' and despite each category representing many centuries of actual time incorporating many subtle changes, these often form the basis of computerised temporal analysis. This may be acceptable within the constraints of digital databases, but GIS places emphasis firmly on visualisation and the shortcomings of both the conceptual model and the digital model become very apparent. At the moment the options for representing change through time in a GIS are similarly limited. The colour coding of sites within a single coverage or within several coverages draped on a DTM can very rapidly degenerate into a visually complex and undecipherable mess. There are also specific problems of representation, the colour coding of a site that spans more than one period, for example. Alternatively, period coverages can be compared visually by simply stacking them or by some other method of display. Langran (1992) presents a general discussion of two-dimensional methodologies used for the representation of time within GIS while Castleford (1992) offers the same within an archaeological framework together with a philosophical foundation for the use of time in archaeology. Van West and Kohler (In Press) document an intriguing methodology for showing change through time using animated video sequences of a series of coverages.

However ingenious the approach with currently available categorical models, it is impossible to overcome the basic problem that time is continuous and must be analysed as such. Because of this requirement, research into truly three-dimensional GIS (sometimes called Geo Scientific Information Systems – GSIS) in which the vertical (z-) axis is continuous just as the x- and y-axes are, is of particular interest to archaeologists. Through the use of new three-dimensional data structures, GSIS allow the building of three-dimensional relationships and topology between spatial data entities. To an extent, in archaeology both depth and temporality are closely interwoven in that the depth at which an artifact or context is found often indicates its temporal sequence relative to other objects or contexts which may occur on top (later), underneath (earlier), or to the side (contemporaneous) although stratigraphy is invariably more

complex. At this point, beyond a stacked series of two-dimensional geographies (Jones 1989; Raper 1989; Turner 1991) the limits of conventional GIS functionality become apparent. Only in a few instances of the dollar rich commercial world of petroleum and gas exploration has GIS been developed and implemented which possess three-dimensional capability, and even here implementation falls short of what can reasonably be envisioned (Harris & Lock 1992). Visualization software moves somewhat toward the exploration of temporality, but stops short of providing the additional features of GIS functionality. In seeking temporal functionality in GIS the demands of archaeologists would clearly indicate a need for three-dimensional capabilities. There exist a variety of ways in which three-dimensional data models can be constructed and it is likely that GIS capability to handle three-dimensional data is not far from being a reality (Belcher & Paradis 1991; Fisher & Wales 1991). A continuous z-axis would permit the construction of dynamic models based on the combined temporal attributes of different archaeological elements within the same site. In this, the possibility of using topology, traditionally used to explore spatial relationships in GIS in two dimensions, to examine spatio-temporal patterns is attractive. This approach may be particularly apposite in the near future in that the development of voxel models may provide the immediate data model with which to model temporality in GIS. These models represent an extension of the traditional GIS raster model. Here, however, the model is composed not of two dimensional cells but three dimensional cubes. This model would appear to have greater potential than the proposed alternatives comprising tessellated plates or interpolated patches linked by b-splines. In the discussion which follows this data model may provide the basis upon which a 'continuous' z-dimension could be explored.

Potential applications of GIS in archaeology are not difficult to envisage. At the intra-site scale the three-dimensional recording of excavated contexts with their stratigraphic relationships implicit within the stored three-dimensional topology represents an obvious outlet for three-dimensional capability. The ability to seek linkages and relationships between archaeological contexts would be possible with the added ability to generate a Harris Matrix from the stored relationships. At the regional level the potential is for the deconstruction of a landscape in terms of its temporal relations between sites. This ability to identify and explore the 'time depth' of a landscape is demonstrated in Figure 1. Here a simple example shows the continuous temporal history of a single spatial location. Using existing two-dimensional GIS software this particular spatial location contains an archaeological site on both of the coverages present for this time span. On the later bronze age coverage, the site is a large enclosure which by the Middle Iron Age has become a smaller hill fort with complex entrance features. The continuous x- and y-axes allow for accurate spatial limits to be defined whereas, in the two-dimensional case, the z-axis is represented by the two categorical time spans of Later Bronze Age and Middle Iron Age which are compressed into temporally 'flat' planes. The implication that the sites remained unaltered for the

entire duration of each period despite both lasting for several centuries is patently inaccurate. Also, the nature of the change through time between the two sites is unknown, it is impossible to show whether it was a gradual linear evolutionary change or a sudden catastrophic change. The only way to visualise change would be to include many more coverages between the two that are illustrated.

Using a true three-dimensional model where the z-axis is continuous, the accurate temporal span of each site can be indicated just as the spatial limits are. It can be seen that the interpretation is now one of initial occupation followed by a period of abandonment of approximately three centuries and then re-occupation in a completely different form of site. It is also possible to assign dates to a site rather than just the categorical value that goes with a two-dimensional coverage. In Figure 1, for example, the earlier site has dates of approximately 1200 to 950 BC, rather than the whole of the Later Bronze Age. Because the continuous z-axis is also available for analysis as well as data visualisation the testing of vertical adjacency between data elements is possible. The spatial query 'find all sites within 2 km of site X' could have the temporal equivalent of 'find all sites within 50 years of site X'. The two together offer a very powerful three-dimensional analytical environment which moves the digital model considerably closer to the real world.

### **Uncertainty, time and temporal GIS**

Uncertainty is an important aspect of human decision-making, especially in a discipline such as archaeology where data is often fragmentary and difficult to classify or date. While uncertainty is invariably included within conceptual models in archaeology it has always been difficult to represent and process within the very precise requirements of digital technology. What has become apparent from early GIS applications in archaeology is that the demands of digital technology to record even site boundary information 'accurately' can be somewhat spurious in terms of implied accuracy. At one level, perceived or affected accuracy can arise simply from the representation of an archaeological feature in the computer or on a hard copy plot. This aspect is already acknowledged within the GIS world, for the routine process of encoding a feature can in itself contribute to a misleading perception of accuracy which the source data and encoding accuracy does not actually support. In the recording of soil distribution maps, for example, the soil type rarely changes as abruptly as the line demarcating the distributions on a map would suggest. There is invariably a transition zone of varying width between the respective soil types, but because of the crudity of both the survey information and current computer spatial data handling technology, this transition is only represented at present as a linear division (Fisher 1987). In archaeology, the problem of defining archaeological site boundaries is long standing. This problem is compounded with GIS for fuzzy archaeology does not lend itself to digital capture in either vector or raster form and yet the need to deal with imprecise or fuzzy archaeological information in both the

spatial and temporal domains is crucial to the effective use of GIS. The method proposed in this paper for handling temporality in archaeological GIS also has merit for addressing this important issue of uncertain temporal boundaries and fuzzy time.

The model proposed here represents one possible approach to handling temporality and uncertainty in archaeological GIS. The model is based upon the application of probability concepts to three-dimensional GIS technology. Both of the sites visualised in Figure 1 have definite temporal boundaries implying that they began and ended abruptly. In archaeological terms, the implication is that evidence exists for a definite beginning and end date for usage of the two sites. In most landscape archaeology this is highly unlikely. Spatial distributions of sites derived from disparate sources including field walking, aerial photography and general accumulated knowledge are unlikely to be accurately dated. Because the emphasis of landscape archaeology is on the understanding and reconstruction of whole landscapes rather than the intense study of single sites, the detailed dating evidence obtained by excavation is not going to be available for much of the data being used. The dating methods used in landscape archaeology are the imprecise methods of the comparative morphology of sites, artefactual evidence from occasional finds or systematic field walking, and the evidence for relative positioning which can be gleaned from physical relationships between adjacent or superimposed sites. The problems associated with the contemporary occupation and use of sites are endemic within current approaches to landscape reconstruction. These problems are exacerbated by the constraints of working with two-dimensional tools such as maps, plans and two-dimensional GIS in which dating is straight-jacketed into categorical classifications.

A more flexible approach is proposed which is based on probability and a continuous z-axis as shown in Figure 2. This is applicable to the modelling of boundary zones between periods where subtle chronological change could be represented rather than simplistic end-to-end categories. In the present example the occupation (or more strictly use so as to include non-occupation sites), span of individual sites within a landscape are being modelled so that at any point in time the probability of use of each site can be calculated. The use of a site is likely to take the form shown in Figure 2 with a core period of certain, or near certain, use with fuzzy zones of decreasing probability of use at either end. If there is definite evidence for the destruction of a site or for its initial construction and use, then either of the ends of the site's lifeline would be abrupt and would indicate a change from  $p(\text{use}) = 1.0$  or close to one, to  $p(\text{use}) = 0.0$ , where  $p(\text{use}) =$  probability of use or occupation of the site. It can be seen from the figure that a site's probability lifeline is not a probability distribution in the statistical sense that it sums to 1.0, but is a value for  $p(\text{use})$  at each point on the z-axis. In this respect the dimensions of the voxel model and the scale of the z-dimension becomes an integral factor in establishing the temporal domain and the value of

p(use). Thus the mechanics of how the values are assigned to the z-axis depends on the data structure and the technology being used.

The digital model can be further refined by incorporating different pieces of dating evidence for any single site. For many sites in a landscape study there will be very little evidence of dating and use although for others there may well be detailed information resulting from excavation. The aim is to produce a p(use) timeline for each site based on the total evidence available. By assigning a p(use) value to each element of evidence for each point on the z-axis a series of individual timelines can be produced as shown in Figure 3. For this hypothetical site there are five pottery groups, six radiocarbon dates, five temporally significant artefacts and the general surface site morphology giving a total of seventeen discrete p(use) elements. Most of the timelines have zones of higher probability towards the centre and fade away at each end. Two of the artefacts, however, provide a terminus *post quem* and a terminus *ante quem* resulting in timelines which are truncated at one end. The inherent flexibility within this model is that the assignment of p(use) values is at the discretion of the archaeologist. Intuitive knowledge and weighting can be incorporated into the p(use) values so that, for example, if one of the five groups of pottery was considered to be more reliable than the other four the probability values could be determined accordingly. Alternatively, if one of the radiocarbon dates were from a suspect context the values could be lowered to reflect this uncertainty and thereby reduce the influence on the overall site p(use) value. The resulting site timeline would not be any recognisable probability distribution but a series of values very likely to fluctuate considerably with the available evidence.

An interesting aspect of this model is whether the overall site p(use) value can be calculated from the individual p(use) timelines. In Figure 3, this is done for the three points on the z-axis representing 100 BC, 300 BC and 500 BC although, of course, being a continuum each point on it would have a value. Also in Figure 3, three different methods of calculating the overall site p(use) value are considered. The first is a straightforward mean of the individual values and the third is the highest value. The second is a weighted mean and is a simple attempt to weight the evidence used according to the totality of evidence available for the site. This is achieved by multiplying the mean by  $n/N$  where  $n$  = the number of dating elements at that date and  $N$  = the total number of dating elements for the site. In consequence, a time point that has few dating elements attached to it is given less weighting than one that has many, although in practice this is not as useful as it may sound. The individual values for 100 BC in Figure 3 show values with a mean of 0.74 which is halved for the weighted mean because half of the timelines do not cross that point on the z-axis. In archaeological terms it is dubious whether dating evidence for one point in time should negate the evidence for another because they are not necessarily related and each stands as a discrete entity. In other words, whether the site was in use at 300 BC does not influence whether it was in use at 100 BC; it is not a reciprocal relationship. Looking at the

individual values and the three overall site values in Figure 3, it seems that the highest p(use) figure is the most useful as both of the other methods dilute individual pieces of secure dating evidence. Assuming that each of the individual values is carefully derived, the highest figure must represent the most confident estimate of site use at that time point. In many respects this mirrors the logic used in phasing contexts during excavation according to contained pottery whereby the latest phase is assigned and any earlier pottery ignored.

Perhaps of greater utility to the archaeologist would be the ability this method permits to undertake simulation exercises using the timelines and P values provided. In instances where sites possess a series of p(use) values then the archaeologist is at liberty to hypothesize as to the likely events, or pace of change, which connects these timelines. In the case of the abandonment of a site, for example, it is possible for the archaeologist to hypothesize a range of responses from, or between, the p(use) values. Such responses might include the very sudden abandonment of a site (catastrophic change), a regularly diminution of use (a linear rate of change), or an increasing rate of abandonment as time went on (a non-linear or exponential rate of change). Such possibilities are clearly speculative at the present time but this method not only permits 'known' temporal flags to be incorporated within the temporal database, but also permits such information to guide the archaeologist in interpreting the site and its relationships to other sites.

It has been emphasised above that one of the important themes within GIS is the visualisation of spatial data which is often difficult to achieve when working with only two dimensions. Because of the constraints of graphics software and the visual complexity of displaying three-dimensional data, a cultural landscape comprising many elements of archaeology each with a depth as well as horizontal dimensions and all to be displayed within a three-dimensional space is an application at the cutting-edge of computer graphics technology. Add to that the desirability to be interactive so that the image can be rotated and viewed from different angles, and a solution is not likely to permeate archaeological practice for some time to come. A glimpse into the future is offered by Reilly and Thompson (1993) who describe Volume Rendering Techniques for displaying massive three-dimensional data-sets using different opacity-levels to view complex images. In the context of the model suggested above, a site could be represented as a three-dimensional column with low p(use) values being shown by increased translucency and high values as high opacity.

## **Conclusion**

Over a relatively few years, archaeological applications of GIS have exposed an interesting relationship between the limits and generation of archaeological theory and those of GIS technology. The challenge of representing time and change through time by the development of

temporal and true three-dimensional GIS is an area of research within mainstream GIS which has important implications for archaeological applications.

Current GIS software offers new and exciting ways of managing, visualising and analysing spatial data albeit within the confines of two-dimensional data-structures and spatial relations. Cultural Resource Management applications tend to be favoured within these restrictions because the time dimension within the data is not critical. The emphasis is on the inventorying of large amounts of spatial and associated attribute data with analysis usually based on identifying and visualising the archaeology of all periods within a specified spatial unit for purposes of planning control. This is a very flat, two-dimensional use of the data and is within the limits of both the archaeological theoretical models and the technology. Applications which are more analytical on the temporal axis are forced to use a categorical model of time with coverages as the current technological equivalent. It is here that the symbiotic relationship between archaeological theory and GIS technology is exposed because developments in the latter are creating the possibilities of developing and testing new theoretical models. GIS and the use of probability models on a continuous z-axis create the technological environment for the testing of archaeological models of continuous rather than categorical time with fuzzy rather than end-to-end boundaries for specific sites and periods together with three-dimensional topology enabling the analysis of three-dimensional spatial relations. It remains to be seen how archaeologists will respond to these new opportunities. In this chapter we have attempted to show the close relationship between the development of archaeological temporal theory and GIS technology and that the latter is not simply an atheoretical tool.

## References.

- Allen, K. M., S. W. Green & E. B. Zubrow 1990. *Interpreting Space: GIS and archaeology*. London: Taylor and Francis.
- Arroyo-Bishop, D. & M. T. Lantada Zarzosa 1992. The Archeo-DATA system: a method for structuring a European Archaeological Information Service (AIS). In *Sites and Monuments*, Larsen, C. U. (ed.), 133–54. Copenhagen: The National Museum of Denmark.
- Belcher, R. C. & A. Paradis 1991. A mapping approach to three-dimensional modelling. In *Three-dimensional Modelling with Geoscientific Information Systems*, Turner, A. K. (ed.), 107–22. Dordrecht: Kluwer Academic Publications.

- Burrough, P. A. 1986. *Principles of Geographic Information Systems for Land Resource Assessment*. Oxford: Clarendon Press.
- Castleford, J. 1992. Archaeology, GIS and the time dimension: an overview. In *CAA91 Computer Applications and Quantitative Methods in Archaeology 1991*, Lock, G. & J. Moffett (eds), 95–106. Oxford: British Archaeological Reports.
- Crawford, O. G. S. 1953. *Archaeology in the Field*. London: Phoenix House Ltd.
- Fisher, P. F. 1987. The nature of soil data in GIS: error or uncertainty. In *Proceedings of International Geographic Information Systems (IGIS) Symposium: the research agenda*, Aangeenbrug, R. T. & Y. M. Schiffman (eds), 307–18. Washington D. C.: NASA.
- Fisher, P. F. & R. Q. Wales 1991. Three-dimensional solid modelling of geo-objects using Non-Uniform Rational B-Splines (NURBS). In *Three-dimensional Modelling with Geoscientific Information Systems*, Turner, A. K. (ed.), 85–105. Dordrecht: Kluwer Academic Publications.
- Harris, T. M. & G. R. Lock 1990. The diffusion of a new technology: a perspective on the adoption of geographic information systems within UK archaeology. In *Interpreting Space: GIS and archaeology*, Allen, K. M., S. Green & E. Zubrow (eds), 33–53. London: Taylor and Francis.
- Harris, T. M. & G.R. Lock 1992. 4-D GIS – whatever next? Paper presented at the International Conference on Computer Applications and Quantitative Methods in Archaeology, University of Aarhus, Denmark.
- Jones, E. R. 1989. Data structures for 3-D spatial information systems. *International Journal of Geographical Information Systems* 1, 15–31.
- Kvamme, K. L. 1989. Geographic Information Systems in regional archaeological research and data management. In *Archaeological Method and Theory 1*, Schiffer, M. B. (ed.), 139–203. Tucson: University of Arizona Press.
- Kvamme, K. L. 1992. Geographic Information Systems and archaeology. In *CAA91 Computer Applications and Quantitative Methods in Archaeology 1991*, Lock, G. & J. Moffett (eds), 77–84. Oxford: British Archaeological Reports.
- Langran, G. 1992. *Time in GIS*. London: Taylor and Francis.

- Lock, G. R. & T. M. Harris In Press. Danebury revisited: an English iron age hill fort in a digital landscape. In *The Anthropology of Human Behavior through Geographic Information and Analysis: an international conference*, Maschner H. D. G. & M. S. Aldenderfer (eds). New York: Oxford University Press.
- Maguire, D. J., M. F. Goodchild & D. W. Rhind (eds) 1991. *Geographical Information Systems: principles and applications*. London: Longman.
- Openshaw, S. 1991. A view on the GIS crisis in geography, or using GIS to put Humpty-Dumpty back together again. *Environment and Planning A* 23, 621–8.
- Raper, J. F. (ed.) 1989. *Three-dimensional Applications in Geographic Information Systems*. London: Taylor and Francis.
- Reilly, P. & R. Thompson. 1993. Experiments with user-friendly volume visualisation and iconographic display methods to explore core data. In *Computing the Past: computer applications and quantitative methods in archaeology CAA92*, Andresen, J., T. Madsen & I. Scollar (eds), 429–39. Aarhus: Aarhus University Press.
- Roorda, I. M. & R. Weimer 1992. Towards a new archaeological information system in the Netherlands. In *CAA91 Computer Applications and Quantitative Methods in Archaeology 1991*, Lock, G. & J. Moffett (eds), 85–8. Oxford: British Archaeological Reports.
- Star, J. & J. E. Estes 1990. *Geographic Information Systems*. Englewood Cliffs: Prentice Hall.
- Turner, A. K. (ed.) 1991. *Three-dimensional Modeling with Geo-scientific Information Systems*. Dordrecht: Kluwer Academic.
- Van West, C. R. & T. A. Kohler In Press. A time to rend, a time to sew: new perspectives on northern Anasazi social development in later prehistory. In *The Anthropology of Human Behavior through Geographic Information and Analysis: an international conference*, Maschner, H. D. & M. S. Aldenderfer (eds). New York: Oxford University Press.
- Wheatley, D. 1993. Going over old ground: GIS, archaeological theory and the act of perception. In *Computing the Past: computer applications and quantitative methods in*

*archaeology CAA92*, Andresen, J., T. Madsen & I. Scollar (eds), 133–8. Aarhus: Aarhus University Press.

### **Figure captions.**

Figure 1. The temporal history of a single spatial location using three-dimensional GIS with possible archaeological interpretation. Note the two points on the z-axis for two-dimensional coverages representing the periods of the Later Bronze Age and the Middle Iron Age.

Figure 2. A probability model of fuzzy temporal boundaries for two sites,  $p(\text{use})$  = the probability of use of the site.

Figure 3. Combining different dating elements from within a site to establish an overall  $p(\text{use})$  for the site. Each dating element has an associated probability and three methods of combining are shown.

Fig. 1

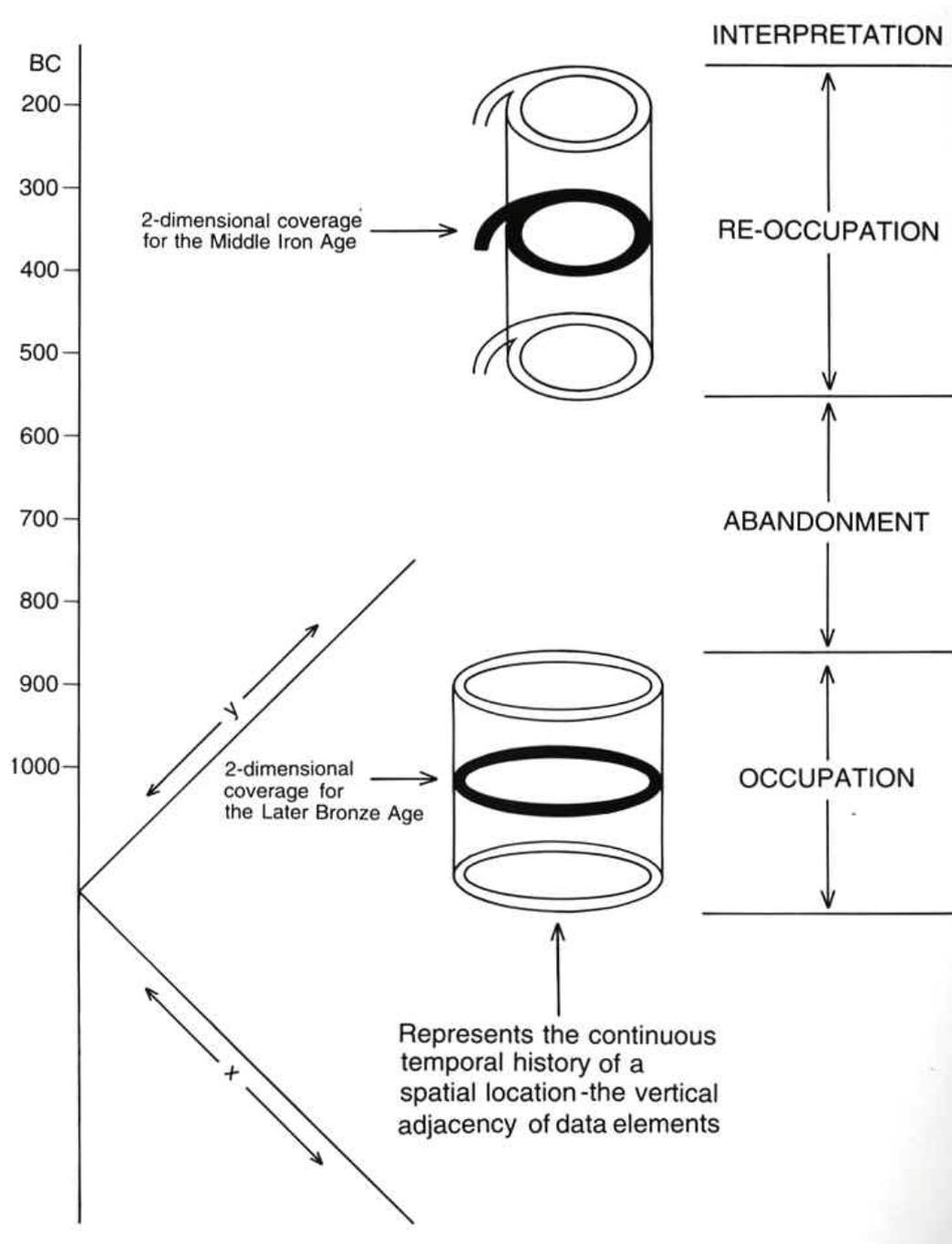


Fig. 1. The temporal history of a single spatial location using three-dimensional GIS with possible archaeological interpretation. Note the two points on the z-axis for two-dimensional coverages representing the periods of the Later Bronze Age and the Middle Iron Age.

Fig. 2

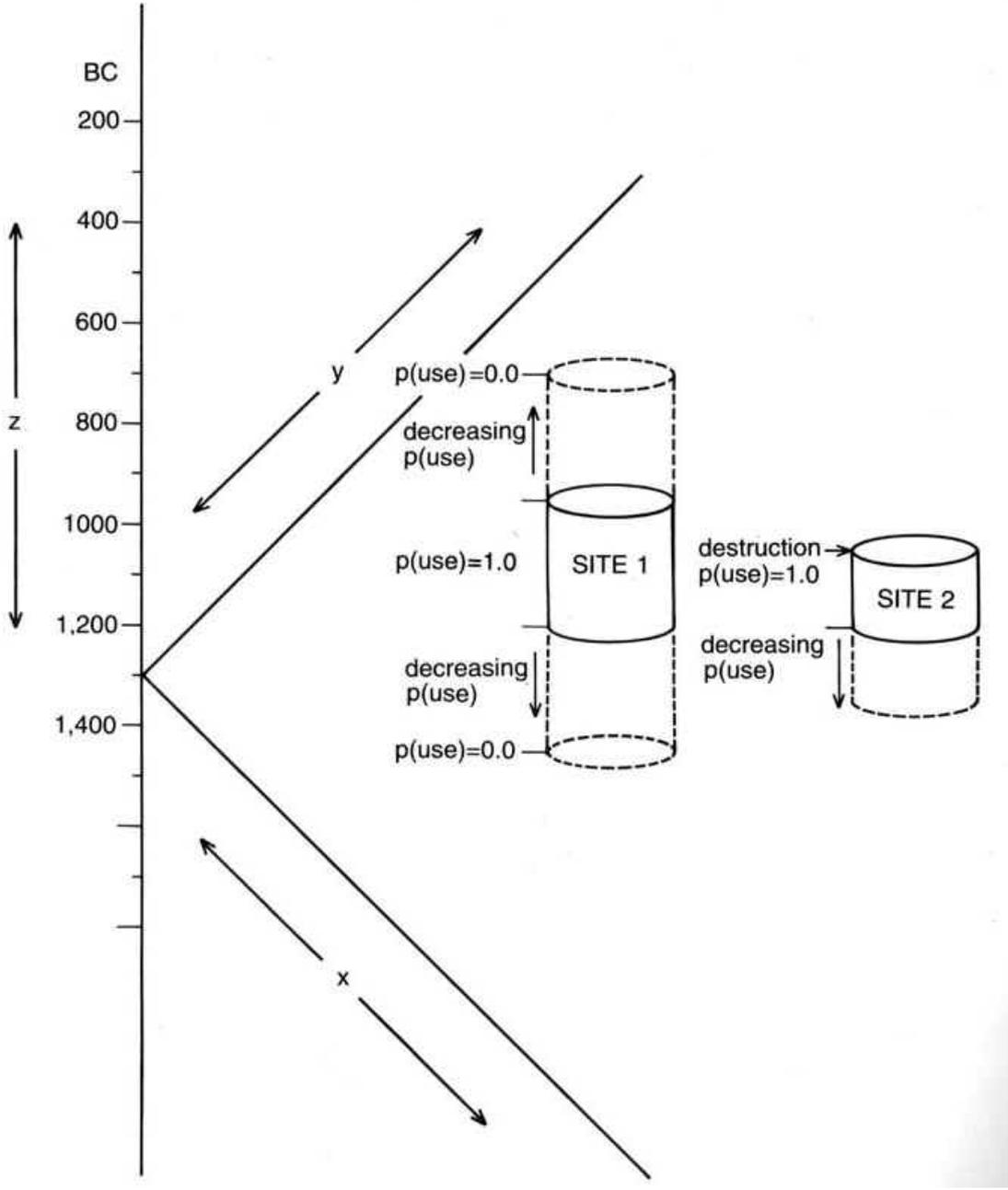


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Fig. 3

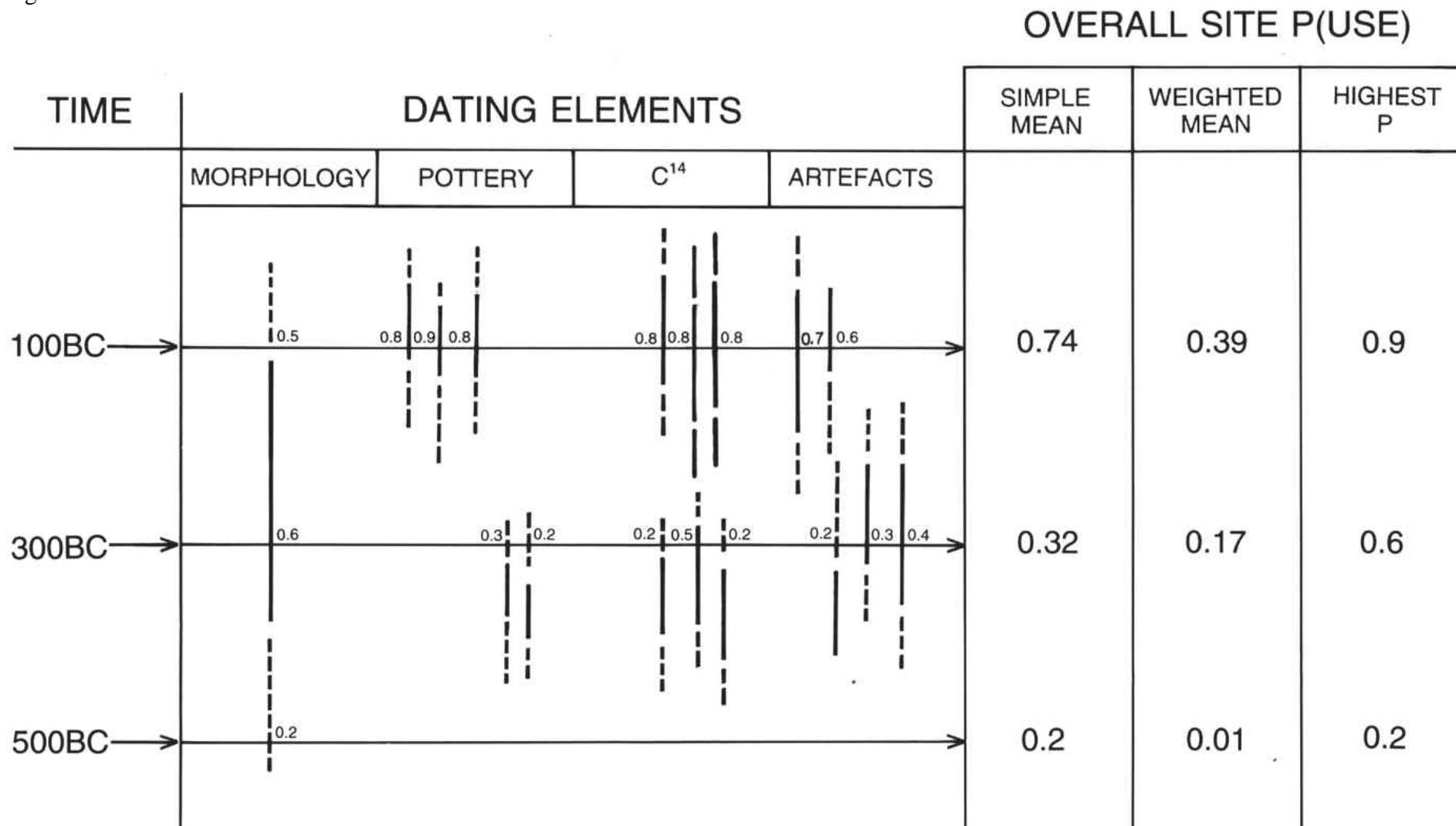


Fig. 3. Combining different dating elements from within a site to establish an overall p(use) for the site. Each dating element has an associated probability and three methods of combining are shown.