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Archaeological computing, archaeological theory and moves towards contextualism

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2.1 Introduction

Several papers published over the last two decades or so have attempted to place developments in archaeological computing within a wider theoretical framework (e.g. Bell *et al.* 1986). These range from the broad approach of Richards (1986) who sees computing as one of many technologies that have influenced the theory and direction of archaeological endeavour, to the more specific theme concerning the relationship between theory and statistical methods. The many and often complex facets of the arguments surrounding the latter are well represented by the collection of papers edited by Aldenderfer (1987), particularly Read (1987).

The present paper adopts a wider view in an attempt to identify linkages between the development of digital technologies and the changing stances of archaeological theory. A brief historical overview suggests a symbiotic relationship between these two apparently disparate areas which has generated the fertile discipline of archaeological computing whose strength is reinforced by the annual occurrence of CAA and its proceedings. Future developments and the implications for different application areas of archaeological computing are then discussed. These are positioned within a perceived trend towards increasing contextualism and data-rich environments which encompass both the technology and the archaeological theory.

2.2 Working with models

Central to the theme of this paper is the concept of working with models. Voorrips (1987) has suggested a useful classification of models used in archaeology based on the distinction between empirical and formal models and combinations of the two. The aim of any model is to simplify something to enable the process of understanding. The drawing of an artefact is an empirical model of a piece of empirical reality but is just as much a model as complex statistical formulae which are a formal model of empirical reality, albeit perhaps at the higher level of social organisation and interaction. It is the use of formal models that interests us here and particularly their ability to represent and interact with archaeological theory, whether a single defined theory or a more general theoretical approach. The use of such models blossomed throughout the 1970s (Clarke 1972; Renfrew and Cooke 1979) and these discussions have always been firmly rooted in considerations of archaeological theory.

The implications of this for archaeological computing are considerable. For archaeological computing to become an integral part of the archaeological process rather than just a set of tools which can be used at appropriate times, there has to be a fundamental link between the computing and the underlying theoretical stance. Whether the theory and/or the link with the computing are explicit and knowingly integrated into the research process is a different problem and not of direct relevance here. Figure 2.1 presents a formal model of models showing an archaeological research process which incorporates the use of computers. It attempts to represent the symbiotic relationships between a series of different models that enable us to make statements about the past. This is left intentionally vague because versions of 'the past' are variable with my, your, our and their pasts all being potentially very different and valid in different ways. An individual's perception of the past is largely determined by unconcious attitudes as well as the theoretical and philosophical stance from which the analysis is performed, as is evident from much recent writing on archaeological theory. Suffice it to say at this point, that which ever particular version of the past is of interest, the aim of archaeology must be to make coherent and meaningful statements about it.

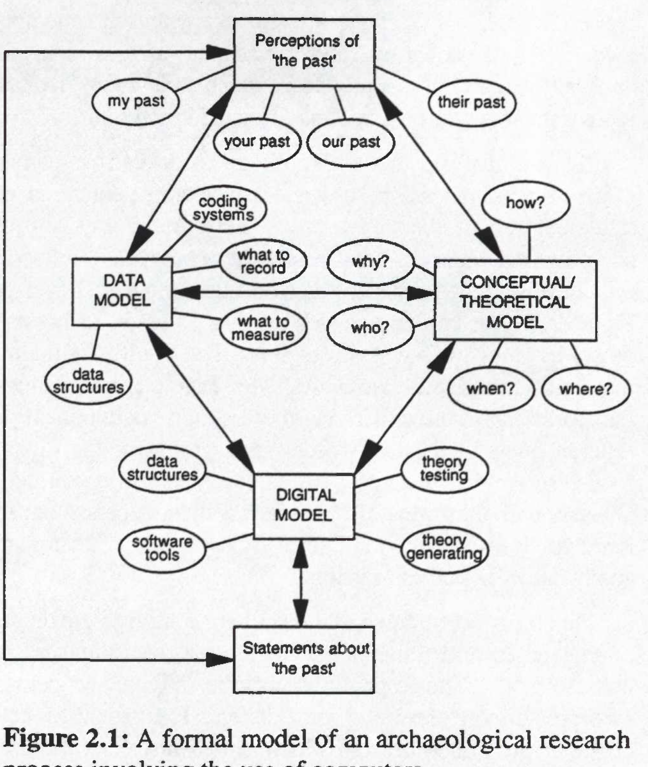

Figure 2.1: A formal model of an archaeological research process involving the use of computers.

The Data Model and the Theoretical Model have always been the basis of archaeological analysis, whether explicitly or implicitly. It is difficult to imagine even the most theoretical of archaeologists not connecting with some data at some point; and conversely the most empirical approach is a theoretical stance in itself. The Data Model incorporates practical and philosophical questions of data structures, coding systems, what to record and what to measure. This brings to the forefront the debate on the objectivity of data and the now generally accepted view that data are theory-laden; whether we can ever have 'things given' or accept that we work with 'things made' (Chippindale forthcoming). The Theoretical Model is the analytical engine that drives the Data Model with questions concerning the who, why, where, when and how of our particular perception of the past. The interaction of these two models which involves theory generation and theory testing in an intuitive, iterative loop represents the formal process of archaeological analysis which is not dependant on the use of a computer. This is similar to a part of Read's discussion (1990, 33) of mathematical constructs and archaeological theory in which he details the relationship between Models of Data and Theory. The current argument suggests that computer-based analyses operate at a further level removed from the target past by an intervening Digital Model.

The Digital Model is necessarily a representation of selected combined elements of the Data and Theoretical Models which are relevant to the analysis or study in hand. There is a very simple but deterministic bottom line to this; if something (most likely to be an entity, a relationship between entities or a concept) can not be represented within a digital environment then it can not be included within a Digital Model and, by implication, in a computer-based analysis. An example of such a limitation is shown by the on-going debate concerning GIS applications in archaeology and the attempts to incorporate cognitive and perceptual spatial data as opposed to environmental data which are more readily representable digitally (Lock and Stancic forthcoming).

The results of working with a digital model can be seen as a virtual or surrogate past which enable the generation of statements about the target past. Performing any sort of computerised analysis illustrates the complex, symbiotic relationships that exist between the three models shown in Figure 2.1. It is an iterative web in which changes to any one model have repercussions throughout. The results of running the digital model, i.e. an analysis, for example, may initiate the rethinking of the underlying theoretical model, inducing a different view of the data model and a rerun of the digital model to complete the loop. This is the essence of exploratory analysis and the 'what if' approach which depends on an iterative web rather than the more rigid structure of confirmatory hypothesis testing.

The properties of the digital model are central to the theme of this paper and fundamental to the use of computers in archaeology. The capabilities of the Digital Model to incorporate more aspects of the Data and Theoretical Models create an environment from which statements about the past are generated. It follows, therefore, that the richer the Digital

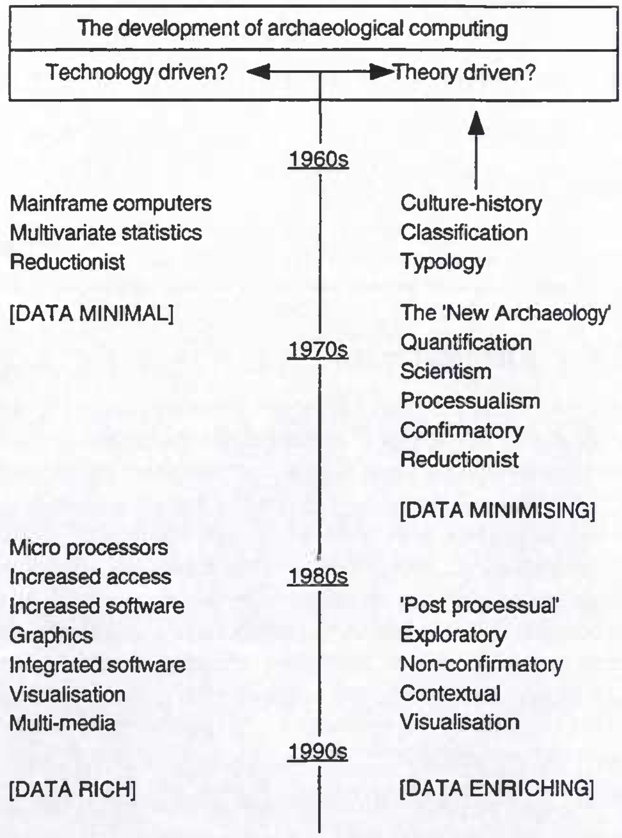

Figure 2.2: A suggested development of archaeological computing.

Model in terms of included data and theory, the richer the resulting statements. This introduces another symbiotic relationship, this time between the technology which determines the capabilities of the Digital Model and changing archaeological theory. This relationship can be viewed within the evolutionary framework of the development of archaeological computing (Figure 2.2), incorporating developments in digital technology in parallel with those in archaeological theory. It is apparent from this that the term archaeological computing as used here refers to not just the technology but also to the underlying archaeological theory driving its use and it would be impossible to 'do' archaeological computing in a theoretical vacuum.

2.3 The evolution of archaeological computing

Way back at the dawn of archaeological computing in the 1960s the available technology consisted of mainframe computers with a limited selection of software. This was a crucial decade in the development of both archaeological computing, archaeological theory and the establishment of a relationship between them. The advent of the so-called New Archaeology, now usually referred to as the processual school, encouraged an explicit use of computer-based quantitative methods. However, such methods were also developing independently of this new, and mainly North American based, movement. In Britain, the work of Hodson and others was concerned with the application of numerical taxonomy to archaeological data, an approach rooted in the existing European tradition of culture-historical archaeology focussing on concerns of classification and culture change based on typologies and seriated sequences (Hodson *et al.* 1966 and many of the papers in Hodson *et al.* 1971). One of the main strengths of mainframe computers during the 1960s was their number crunching abilities and the running of multivariate statistical software. This offered a severely limited data-minimal digital model in which to operate although it was adequate for the contemporary data-minimising theory. The data requirements of the software were a numerical matrix and, therefore, reductionist in the extreme. This mirrored the theoretical precepts of classification and typology involving the identification and comparison of diagnostic traits, usually of isolated, de-contextualised groups of artefacts or, at best, artefacts within discrete archaeological contexts.

This comfortable match between the available digital model and the prevailing theoretical paradigm was also applicable to much of the archaeological computing advocated by the processualists. Quantification, and by implication a computer-based approach, became inextricably linked to the reductionist scientism seen to be central to a processual approach to explaining the past. This was made explicit very early in the debate with the introduction of multivariate statistics by the leading proponent of the New methodologies (Binford and Binford, 1966). Intrinsic to this paradigm was a belief in objectivity and a belief that the processes, structures and behaviour that formed the archaeological record could be reached via appropriate methodologies, of which hypothetico-deductivism, hypothesis testing and quantification formed an important part. Of course not all contemporary archaeologists, even those at the forefront of archaeological computing, agreed with rigid processual approaches, and it is refreshing to re-read Doran and Hodson (1975, Chapter 13) for an alternative view. Other alternative views developed through the 1980s into what is generally now labelled Post-processual archaeology which can be seen as part of the wider post-modernist movement.

Post-processual archaeology is, in effect, not so much an integrated school of thought rather than a divergent series of theoretical approaches united mainly by their critique of processualist methods. It is way beyond the theme of this paper (and this author!) to detail developments in archaeological theory other than to identify aspects which are relevant to archaeological computing. However, it is important to note that this is not a central theme of most post-processual writing, although it is recognised that quantitative methods do have a part to play in such methodologies (Shanks and Tilley 1987). The divergence of approaches which shelter beneath the post-processualist umbrella make it difficult to generalise on the perceived role of computing. In a recent review (Barrett 1994, Chapter 7) it gets no mention at all, whereas in a paper which attempts to forge links between processual and post-processual methodologies concerning sociocultural theory (Cowgill 1993), quantitative methods are seen to be central. Of course post-processualism is not the end of the story. The development of archaeological theory is an endless continuum and reactions to aspects of post-processual thought have been many and varied. Both of the last two citations above can be seen as examples of moving the debate beyond post-processualism and a recent collection of papers (Yoffee and Sherratt 1993) presents a range of alternative theoretical positions.

One theme which can be identified within much writing on post-processual archaeology is that of context and contextualism. Hodder (1986; 1987), for example, has shown the importance of context in terms of both the context of data and the social and cultural context of the analyst (although see Barrett 1987 for an alternative view of what contextualism is about). It has been argued by Kohl (1993, 13) that 'knowledge is never absolute nor certain but must be contextualised'. Of course the concept of context is open to many different interpretations and applications but with reference to the process suggested in Figure 2.1, context is integral to the Digital Model. In this sense context is not just concerned with the inclusion of more and varied data but also with the links and relationships between data which can be stored and studied. The knowledge we produce generates statements about the past and in a computer-based analysis these are a product of the Digital Model. It follows, therefore, that data-rich digital models and data-enriching theoretical approaches are symbiotically linked within a methodology which acknowledges the primacy of contextuality. Figure 2.2 suggests that developments in information technology over the last three decades have been steadily moving towards increasingly data-rich digital environments. The parallel with trends in archaeological theory is not trivial and represent a shift from theory-driven deductive methods which can operate in data-minimal environments to data-driven inductive approaches which are data hungry. This is mirrored in changing sociocultural theory and views of culture from something that can be reduced to a series of structures, laws and quantifiable patterns to something that is a much more complex system of interacting values and beliefs. A worldview, in fact, that is not rigidly structured and minimising but is contextual, the study of which demands data-rich contextual models.

2.4 Towards data-rich contextualism.

It is possible to illustrate this trend towards contextualism in archaeological computing with specific examples, starting with databases which are probably the most widely used software tool in archaeology. Early flat-file database structures were rigid data-minimal models which constrained the representation of relationships between entities. Of the subsequent data models that have emerged, the relational model has found favour in allowing a much richer and theoretically satisfying representation of entities, attributes and relationships. Of the many examples in archaeology, the relational model of excavation recording developed by Andresen and Madsen (1992) is an excellent example of this move towards data-richness. The work of Goodson (1989) is an early example of the inclusion of images within database structures and can be seen as a step towards the exciting and very rich digital environments of interactive multimedia. The importance of these technological developments for contextuality is not just the vastly improved range of data-types that are brought into play within an integrated digital environment but the concept of non-linear access and the complexity of links between data that are fundamental to multimedia authoring (Rahtz *et al.* 1992 demonstrate this with the example of excavation reports). Large multimedia databases can include not only images and text but also moving video, animation and sound. Archaeology operates within a multi-dimensional world which is analogous with the concept of contextuality and the functionality of digital multimedia. It follows from this that multimedia data, which are infinitely cross-linked within multi-dimensional hyperspace, reflect changes in theoretical approaches by encouraging data-driven analyses rather than the theory-driven deductive methods enforced by data-poor digital models.

For databases with a spatial component, and especially those purporting to be analytical rather than purely representational, we need to examine the past, current and future role of Geographic Information Systems in archaeology. GIS is a multi-million dollar bandwagon that has been gathering momentum across international markets, as well as within the rather smaller world of archaeology (Allen *et al.* 1990). This is based partly on the appeal of the data-rich spatial environment on offer and on the powers of spatial visualisation afforded (Lock and Harris 1992). Despite the tremendous amount of hype that has been generated around GIS applications in archaeology, one of the most interesting debates at the moment concerns the poverty of the available digital model and its mismatch with current theoretical models, especially concerning landscape archaeology (discussed in detail by Gaffney and van Leusen, forthcoming). It is no longer of great novelty in terms of research methodology to know that certain types of sites can be shown to display a locational preference to a certain altitude/soil type/slope/aspect/distance from water or any other environmental correlate. This deterministic analytical approach can be seen in theoretical terms as a throwback to processualism and a data-minimal digital model. The debate concerning the theoretical validity of GIS has raged in geography for some time (Openshaw 1991) where the technology has been seen by some as the 'quantifiers revenge' over the post-modernists. The deterministic origins of GIS in archaeology are not difficult to trace to the initial uses of the technology for the predictive modelling of site location within Cultural Resource Management projects. The literature on predictive modelling is extensive but see Judge and Sebastian (1988), and Warren (1990) for the fundamentals and Brandt *et al.* (1992) and Kvamme (1992) for the persistence of the methodology.

Current theoretical models of social theory and cognitive aspects of space and landscape are at odds with the limited digital model offered by current GIS software. Modern human spatial cognition is extremely difficult to understand and represent (Mark 1993) and the problems are multiplied many-fold when dealing with past peoples (Zubrow 1994). It is very pertinent here to repeat the statement in section 2.2 above, that if something cannot be represented digitally then it cannot be included in the digital model and by implication in a computer-based analysis. This is the problem with variables relevant to much cognitive and social landscape theory: they are difficult to isolate, measure and record digitally. The theoretical model has forced the existing digital model to its limits and found it wanting. Archaeologists have been quick to attempt compromise and have recognised viewshed analysis as the most promising aspect of the current digital model in an attempt to bridge this gap (Wheatley 1993 and several papers in Lock and Stancic forthcoming). There is no doubting that the future of GIS lies in moves towards increasingly data-rich environments and increasing multi-dimensionality. This can be seen in terms of multimedia GIS which are showing great potential (Buttenfield and Weber 1993) and for the more specific improvement in dimensionality inherent within truly 3-dimensional GIS (Raper 1989; Turner 1991). One of the exciting implications of the latter for archaeology is the development of temporal GIS where time and change through time are represented on a continuous z-axis (Lock and Harris forthcoming). This would free analysis from another severe restriction of the current GIS digital model which forces time into a categorical theoretical model through the use of coverages. The promise of continuous time together with fuzzy temporal and spatial boundaries is part of the move towards the increasing richness of future GIS and, perhaps, an improved fit between the digital and theoretical models.

Statistics were a part of the central creed of processual methodologies and their manipulation of the data-rich digital models of post-processualism is perhaps less obvious than for other areas of archaeological computing. It has been argued above that GIS hold the potential for data-rich spatial analysis and that should include spatial statistics. A major failing of traditional spatial statistical methods (Hietala 1984 for example) is that they are too reductionist and incapable of incorporating background, or contextual, information. To reduce complex archaeological spatial reality to a series of points, then test for randomness and produce a probability value has failed to capture the interest of most archaeologists looking for spatial interpretations of their data. GIS should offer a much more productive environment for spatial statistical analysis although most software available at the moment is surprisingly lacking in this area. Kvamme (1993) has been a pioneer in attempting to integrate spatial statistics into archaeological GIS applications. In a recent short article (Kvamme 1994) he comments on the relationship between the theory-down deductive reasoning of formal methods and the exploratory, data-up inductive approaches encouraged by visualisation. He argues for an integration of the two to create a 'healthy spatial archaeology' which must utilise the data-rich digital models described here rather than the data-minimal models upon which traditional spatial statistics operated.

Various types of multivariate statistics, usually based on some kind of similarity matrix of cases and variables, are equally reductionist and were equally central within processual methodologies. It is of interest that the latest textbook of multivariate techniques includes 'Exploratory' in its title (Baxter 1994) and the author stresses the point that such methods need not be aligned with any particular theoretical stance thus avoiding the dangers of 'throwing methodological babies out with the theoretical bathwater' (*ibid*, 8). Twenty years after the first book of its kind (Doran and Hodson 1975), it is difficult at first to see how multivariate statistical methods have evolved to fit into the general trend towards contextuality and the data-rich digital models described here. Of course, some problems are suited to statistics by being purely analytical rather than requiring a wider context. Perhaps quantitative methods really are sufficiently different to the rest of archaeological computing to warrant the separatist title of this volume and its associated conference. Having said that, there is the potential of future convergence between the data-rich models of other forms of archaeological computing and multivariate statistical analysis and the key words for this link are multidimensionality, visualisation and exploratory. A promising route towards this future is shown in an enlightening paper by Openshaw (1994) which is one of several discussing spatial analysis and GIS (Fotheringham and Rogerson 1994).

Openshaw's theme is one of data-driven exploratory analysis within a data-rich multidimensional digital model. He outlines Tri-Space Analysis which utilises variables inherent within Geographic Space, Temporal Space and Attribute Space thus forming the totality of the GIS environment open to pattern-spotting procedures. The analytical power is invested in a STAM (Space-Time-Attribute-Machine) which in essence operates a search-everywhere philosophy. A refinement of this involves the concept of A.L. (Artificial Life) which is a branch of A.I. (Artificial Intelligence) where a STAC (Space-Time-Attribute-Creature) in the form of a hyper-sphere roams around the database feeding on data and adapting to its environment via a genetic algorithm. In simple analytical terms this means testing different groups of variables within the multidimensional database for patterning, whether that is deviation from randomness or patterning according to any other definition. As the analysis proceeds so the algorithm controlling it can change its aims according to the data it processes. The other important aspect of this approach is that it brings AI, an area of archaeological computing which has declined in acceptance after a period of intense interest, into line with the general trend towards data-rich digital models and contextuality. Of course, this is not suggesting that within the next few years every archaeological unit will be employing artificial life to perform its post-excavation work, but it does reinforce a convergence based on this trend and the following quote from Openshaw is particularly apposite:

> "Suddenly, the opportunity exists to take a giant step forward not by becoming clever in an analytical sense, but purely by becoming cruder and more computationally oriented in a way that allows the computer to do most of the work. It is almost as if computer power is to be used to make up for our ignorance of the nature and behaviour of the complex systems under study." (Openshaw 1994, 91).

This is not suggesting that brute computer force is a substitute for theory or thinking, but that the digital models available today are approaching the richness of theoretical approaches.

2.5 Conclusions.

In the collection of papers mentioned above (Yoffee and Sherratt 1993), Bradley (1993) talks of a loss of nerve in archaeology with a polarisation between two opposites. On the one hand are the scientists who use ever more specialist equipment and techniques to perform increasingly detailed analyses, usually on artefacts, and generally add little to the wider understanding of past human behaviour. On the other are the post-processualist theoreticians who appear to have become so disillusioned with the archaeological record and insist on such introspection that they have become the PC police of archaeology (not IBM compatible!). The majority of working archaeologists are suspended somewhere in the middle feeling decidedly uncomfortable with a move in either direction. Bradley's plea is for a rejuvenation in archaeological creativity, to be able to bridge the gap between the alienating extremes of formal scientific methods and theoretical ideology. Such creativity, I suggest, depends on a fertile mix of data and theory within an environment that encourages unrestricted interaction between the two. It is my hope that as technological limitations fade into the background, so archaeological computing powered by ever more data-rich and contextual digital models, can play its part in the archaeological theory of tomorrow.

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References

ALDENDERFER, M. S. (ed.) 1987. *Quantitative Research In Archaeology. Progress And Prospects*, Sage Publications, New York.

ALLEN, K. M. S., GREEN, S. W. & ZUBROW, E. B. W. (eds.) 1990. *Interpreting Space: GIS and archaeology*, Taylor and Francis, London.

ANDRESEN, J. & MADSEN, T. 1992. 'Data structures for excavation recording. A case of complex information management' in C. U. Larsen (ed.) *Sites and Monuments. National Archaeological records*, 49–67. The National Museum of Denmark, Copenhagen.

ANDRESEN, J., MADSEN, T. & SCOLLAR, I. (eds.) 1993. *Computing the Past. CAA92 Computer Applications and Quantitative Methods in Archaeology*, Aarhus University Press, Aarhus.

BARRETT, J. C. 1987. 'Contextual archaeology', *Antiquity*, 61, 468–473.

BARRETT, J. C. 1994. *Fragments from Antiquity. An archaeology of social life in Britain, 2900–1200 BC*, Blackwells, London.

BAXTER, M. J. 1994. *Exploratory Multivariate Analysis in Archaeology*, Edinburgh University Press, Edinburgh.

BELL, J. A., LOCK, G. R. & REILLY, P. (eds.) 1986. *Formal Methods, Quantitative Techniques and Computer Applications in Theoretical Archaeology*, Science and Archaeology, 28 (Special Edition).

BINFORD, L. R. & BINFORD, S. R. 1966. 'A preliminary analysis of functional variability in the Mousterian of Levallois facies', *American Anthropologist*, 68, 238–295.

BRADLEY, R. 1993. 'Archaeology: the loss of nerve' in N. Yoffee & A. Sherratt (eds.), 131–133.

BRANDT, R., GROENEWOUDT, B. J. & KVAMME, K. L. 1992. 'An experiment in archaeological site location: modelling in the Netherlands using GIS techniques', *World Archaeology*, 24, 268-282.

BUTTENFIELD, B. P. & WEBER, C. R. 1993. 'Visualisation and Hypermedia in Geographical Information Systems' in Medyckyj-Scott and Hearnshaw (eds.), 136–147.

CHIPPINDALE, C. (forthcoming). 'Capta (not Data), Information, Knowledge and Understanding' in S. Ross (ed.) *The problems and Potentials of Electronic Information for Archaeology*, The British Academy, London.

CLARKE, D. L. (ed.) 1972. *Models in archaeology*, Methuen, London.

COWGILL, G. L. 1993. 'Distinguished Lecture in Archaeology: Beyond Criticizing New Archaeology', *American Anthropologist*, 95 (3), 551–573.

DORAN, J. E. & HODSON, F. R. 1975. *Mathematics and Computers in Archaeology*, Edinburgh University Press, Edinburgh.

FOTHERINGHAM, S. & ROGERSON, P. 1994. *Spatial Analysis and GIS*, Taylor and Francis, London.

GAFFNEY, V. & VAN LEUSEN, M. (forthcoming). 'GIS, Environmental Determinism and Archaeology: a parallel text', in G. Lock & Z. Stancic (eds.).

GOODSON, K. J. 1989. 'Shape information in an artefact database' in S. P. Q. Rahtz & J. D. Richards (eds.), *Computer Applications and Quantitative Methods in Archaeology 1989*, 349–361, British Archaeological Reports International Series 548 (2 volumes), Oxford.

HIETALA, H. J. (ed.) 1984. *Intrasite spatial analysis*, New directions in archaeology, Cambridge University Press, Cambridge.

HODDER, I. 1986. *Reading the Past: current approaches to interpretation in archaeology*, Cambridge University Press, Cambridge.

HODDER, I. (ed.) 1987. *The archaeology of contextual meaning*, Cambridge University Press, Cambridge.

HODSON, F. R., SNEATH, P. H. A. & DORAN, J. E. 1966. 'Some experiments in the numerical analysis of archaeological data', *Biometrika*, 53, 311–324.

HODSON, F. R., KENDALL, D. G. & TAUTU, P. (eds.) 1971. *Mathematics in the Archaeological and Historical Sciences*, Edinburgh University Press, Edinburgh.

JUDGE, J. W. & SEBASTIAN L. 1988. *Quantifying the Present and Preserving the Past: Theory, method and Application of Archaeological Predictive Modelling*, US Department of the Interior, Denver.

KOHL, P. L. 1993. 'Limits to a post-processual archaeology (or, The dangers of a new scolasticism', in N. Yoffee & A. Sherratt (eds.), 13–19.

KVAMME, K. L. 1992. 'A Predictive Site Location Model on the High Plains: An Example with an Independent Test', *Plains Anthropologist*, 56(2), 19–40.

KVAMME, K. L. 1993. 'Spatial statistics and GIS: an integrated approach', in J. Andresen *et al.* (eds.) 91–103.

KVAMME, K. L. 1994. 'Computer visualization vs. statistics: how do they fit together?', *Archaeological Computing Newsletter*, 38, 1–2.

LOCK, G. R. & HARRIS, T. M. (forthcoming). 'Analyzing change through time within a cultural landscape: conceptual and functional limitations of a GIS approach', in P. Sinclair (ed.) *Urban origins in eastern Africa*, One World Archaeology series, Routledge, London.

LOCK, G. R. & STANCIC, Z. (eds.). (forthcoming). *Archaeology and Geographic Information Systems: A European Perspective*, Taylor and Francis, London.

MEDYCKYJ-SCOTT, D. & HEARNSHAW, H. M. 1993. *Human Factors in Geographical Information Systems*, Belhaven Press, London.

MARK, D. M. 1993. 'Human Spatial Cognition', in Medyckyj-Scott & Hearnshaw (eds.), 51–60.

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, 621–628.

OPENSHAW, S. 1994. 'Two exploratory space-time-attribute pattern analysers relevant to GIS', in S. Fotheringham & P. Rogerson (eds), 83–104.

RAHTZ, S., HALL, W. & ALLEN, T. 1992. 'The development of dynamic archaeological publications', in P. Reilly and S. Rahtz (eds), 360–383.

RAPER, J. F. (ed.) 1989. *Three dimensional applications in Geographic Information Systems*, Taylor and Francis, London.

REILLY, P. & RAHTZ, S. (eds.). 1992. *Archaeology and the Information Age. A global perspective*, One World Archaeology Series 21, Routledge, London.

RICHARDS, J. D. 1986. 'Computers in Archaeological Theory and Practice', in Bell *et al.* (eds.), 51–55.

READ, D. W. 1987. 'Archaeological Theory and Statistical Methods: Discordance, Resolution, and New Directions', in M. S. Aldenderfer (ed.), 151–184.

READ, D. W. 1990. 'The utility of mathematical constructs in building archaeological theory', in A. Voorrips (ed.), 29–60.

RENFREW, C. & COOKE, K. L. (eds.) 1979. *Transformations: Mathematical approaches to culture change*, 145–167, Academic Press, New York.

SHANKS, M. & TILLEY, C. 1987. *Re-Constructing Archaeology*, Cambridge University Press, Cambridge.

TURNER, A. K. (ed.) 1991. *Three dimensional modelling with Geoscientific Information Systems*, Kluwer Academic Publications, Dordrecht.

VOORRIPS, A. 1990. *Mathematics and Information Science in Archaeology: a flexible framework*, Studies in Modern Archaeology, HOLOS-Verlag, Bonn.

WARREN, R. 1990, 'Predictive modelling of archaeological site location', In K. M. Allen *et al.* (eds.) 201–215.

WHEATLEY, D. 1993. 'Going over old ground: GIS, archaeological theory and the act of perception', in J. Andresen *et al.* (eds.), 133–138.

YOFFEE, N. & SHERRATT, A. 1993. *Archaeological Theory: who sets the agenda?* New Directions in Archaeology, Cambridge University Press, Cambridge.

ZUBROW, E. B. W. 1994. 'Knowledge representation and archaeology: a cognitive example using GIS', in C. Renfrew and E. B. W. Zubrow (eds.) *The Ancient Mind. Elements of cognitive archaeology*, New Directions in Archaeology, Cambridge University Press, Cambridge.