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MORTIMER WHEELER ARCHAEOLOGICAL LECTURE

THE SERC EXPERIMENT IN SCIENCE-BASED ARCHAEOLOGY

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I HAVE had the rare privilege of visiting a new world with expert guides; 'New men, strange faces, other minds' would have been a suitable title to describe the experience but that was the title of J. D. Clark's 1981 lecture. Other titles in the Mortimer Wheeler Archaeological Lecture series did not help me to choose a theme, and I conclude that the Council of the British Academy had something different in mind this year.

I hope to give a scientist's perspective of the opportunities which already exist for science in archaeology. For my scientific colleagues I shall describe some experimental results in archaeology which are as fundamental, interdisciplinary, and wondrous as their own; for my new friends and acquaintances in archaeology I hope to describe means by which the archaeological community might proceed to the next phase of the experiment. Finally, and especially for those who administer parts of the science vote, I will describe just one important opportunity, partly archaeological, which is being missed because the research community is unable to co-ordinate access to current facilities in an appropriate way.

Ten years ago the Science and Engineering Research Council (SERC) experiment began when a group representing archaeology, led by the British Academy, convinced the Advisory Board for the Research Councils (ABRC) that a new way should be found to encourage and support research into the development and extension of scientific methods in archaeology. This approach coincided with Sir Sam Edwards' initiative to identify areas of scholarly scientific activity which were failing to attract support within the research council system. The Science Research Council (SRC) assumed responsibility for the funding of science-based archaeology in the universities and polytechnics and on 1 July 1976 the Science-based Archaeology Committee (SBAC) was appointed under the chairmanship of Professor J. D. Clark, CBE (with five assessors from outside bodies, more than any other committee of the SRC except the Council itself!). Whereas a small number of research grants had been awarded by the SRC Scholarship Committee in 1974 and 1975, the establishment of the Science-based Archaeology Committee determined a turning point in the funding of archaeology in British academic institutions. By 1979–80 the annual funding rate had increased tenfold to about £400,000 and it has remained at that level in cash terms ever since. The growth in postgraduate awards during the last decade paralleled that in research grants and now stands at about £200,000 per annum.

In view of this special initiative, which generated a significant new resource base, it is surprising that none of the annual reports of the Science Research Council in the formative years 1974–9 mentions science-based archaeology except in the statistical appendices and the same is true for the Science and Engineering Research Council's first corporate plan published in December 1985. During 1985 I was asked by the Science Board of SERC to chair a panel to review their arrangements for funding science-based archaeology (SERC, 1985). The review panel quickly established a schedule for the technical part of its work but was repeatedly frustrated in attempting to analyse the relevance of the SBAC objectives to the needs of archaeological science (and of archaeology as a whole) and to decide the extent to which SERC should be responsible for the allocation of funding in archaeological science. These parts of the panel's terms of reference relate to some of the most important issues for the future of science in archaeology. Although outside the strict terms of reference of any research council, the structure of archaeology, the nature of the subject, and its needs must be understood by funding organizations. Just as research grants in traditional science subjects are directed into 'well-founded laboratories', so funds for science-based archaeology should be allocated to research workers tackling important problems in archaeology using appropriate scientific methods; or so the theory runs.

Archaeology in the United Kingdom

There are literally hundreds of organizations involved in archaeology in the United Kingdom but few are in a position to determine the objectives and needs of archaeology as a whole.

From the partial listing of organizations (given in Table 1) and their available resources (given in Table 2) it is clear that there are very wide-ranging interests and a considerable resource base in archaeology. The SERC's contribution is now seen in context as only 3–4 per cent of the total. Nevertheless, many archaeologists attach great importance to the development and extension of scientific methods into archaeology and in those terms the SERC programme has achieved remarkable results considering its rather small share. We were able to review the work which

TABLE 1. *Organizations for archaeology in the United Kingdom*

British Academy	
The Royal Society	
Government Agencies	Department of the Environment: Historic Buildings and Monuments Commission Department of Education and Science: The Universities Grants Committee Scottish Development Department Welsh Office Department of Education in Northern Ireland Survey of Northern Ireland Royal Commissions on Ancient and/or Historical Monuments in England, Wales and Scotland Ordnance Survey
The Research Councils	Science and Engineering Research Council: Science-based Archaeology Committee Natural Environment Research Council Economic and Social Research Council
The Universities	17 universities offer undergraduate and higher degrees in Archaeology 5 universities offer subsidiary courses only
Local Government	Association of County Archaeologists
Museums	British Museum National Museum of Antiquities of Scotland National Museum of Wales Ulster Museum Approximately 300 other museums
Rescue Archaeology Units	Standing Conference of Unit Managers
Archaeological Societies	Council for British Archaeology The Society of Antiquaries of London The Society of Antiquaries of Scotland Approximately 80 other societies

TABLE 2. *Archaeological funding in the United Kingdom*

	Estimates (1985) £000's p.a.
The British Academy	175
Historic Building and Monuments Commission	5000
The University Grants Committee	3000
Scottish Development Department	400
Welsh Office	300
Royal Commissions: England	2500
Wales	600
Scotland	750
Manpower Services Commission	several 1000s
Science and Engineering Research Council	600
Total of other sources	100

Source: SERC, 1985.

had been funded by the SBAC as a series of demonstrations and to find considerable success, but many fundamental questions about the future development of archaeology remain to be answered. Who can formulate policy and define priorities for archaeology as a whole? What are the objectives of the next phase of the SERC experiment in funding science-based archaeology? Are the present arrangements for archaeological teaching and research in the universities matched to the needs of archaeology as a whole?

At the time of the review there was no answer to the first question. The panel recommended the appointment of a coordinator for science-based archaeology to procure proposals in areas requiring research, to liaise extensively throughout the archaeological community, and to propose structural changes in archaeology which will assist all the bodies involved in science-based archaeology. The British Academy, English Heritage and SERC have now agreed to support jointly such a post—a very important development for the future of archaeology in the United Kingdom and not just for science-based activities.

The SERC panel review identified a number of areas in which insufficient work had been funded before 1984 (Table 3). One objective of the next phase of science-based archaeology funding would clearly be to demonstrate the value of science-based work in prospecting methods, computation and statistics, conservation science, palaeopedology, and environmental archaeology.

Within a budget which is likely, on optimistic assumptions, to remain static for the forseeable future the question occurs of

TABLE 3. *SBAC Research Grant statistics 1978–84*

	No. of Grants	£000's	%
A. Archaeological dating techniques	29	1317.0	53
B. Analytical methods	31	639.9	25
C. Applications of statistics and computing	8	118.4	5
D. Prospecting methods	0	0	0
E. Biological and environmental techniques	16	418.7	17
	78	**2486.0**	**100**
F. Conservation science	—	—	—
G. Palaeopedology	—	—	—
H. Environmental archaeology	—	—	—

Theme D was not funded even though applications had been received. Themes F, G and H were identified as important during the review.

Source: SERC, 1985.

further funding for dating techniques, analytical methods, and biological and environmental techniques whose value has already been demonstrated in part. In professional archaeology outside the universities, for example in the British Museum and in the Ancient Monuments Laboratory of English Heritage at Fortress House, wide-ranging expertise in science-based archaeology has already been incorporated into the activities of archaeological teams. In my view that must now happen on a comprehensive basis in the teaching and research departments of some universities. This view relates too to the third question.

To support this view I will describe in some detail three or four successful programmes from the SBAC list, all, by chance, concerned with dating techniques. They are chosen to illustrate the variety of relevant science, to underline the common theme that wide application is achieved only when both the scientific and archaeological provenances are clearly understood and to illustrate that in many successful collaborations **both** disciplines **and** science as a whole stand to gain. Attitudes of archaeologists towards the value of a science-based input to their studies vary widely; I want to concentrate on the necessary nature of those contributions and on the structural changes which will be necessary if the full benefits of scientific methods are to be realized in archaeology.

During the demonstration phase of SBAC funding many highly praised programmes were achieved by an archaeologist working with a scientist who had particular expertise or instrumentation at his disposal. While this can be successful in a demonstration project it is clear that one can and must do better if a method is to be routinely used with confidence. The introduction to a recent book (Parkes, 1987) demonstrates very clearly some of the problems which may arise if collaborators are totally ignorant of each others' fields.

> . . ., ideally, when planning a project the archaeologist should decide which scientific techniques are likely to be of use in helping to solve the problems under consideration. . . . The scientist will not be pleased if, having put much effort into obtaining a date which upsets the archaeologist's hypothesis, he is then informed that maybe the sample had been reused or had migrated from a different layer.

To my mind these words do not relate to a potentially successful collaboration but to an unsuccessful customer–contractor relationship.

Some examples of applications in archaeology

Thermoluminescence dating

I choose thermoluminescence dating as my first topic to illustrate the very broad science base which is necessary for the reliable application in archaeology of what is in principle a simple technique. Although thermoluminescence as a physical phenomenon has been known since 1663 when Robert Boyle reported that diamonds glowed in the dark when warmed (Boyle, 1663), the origin of this energy, ionizing radiation, was unknown a century ago and the idea that thermoluminescence might be useful for archaeological dating was first mooted in the 1950s. Only recently has the technique reached maturity as evidenced by the publication of comprehensive textbooks (Fleming, 1979; European Science Foundation, 1983; Aitken, 1985) and the provision of 'routine' dating services (SERC Reports).

When materials are irradiated atoms become ionized, that is, they lose one or more electrons. In non-metals the ionized state is metastable and in practice there may be many different ionized centres, simultaneously present, especially when the host material also contains impurities. After a time, when the electron and ion recombine, the ionization energy is released as light. Depending on the particular material, the wavelength of the emitted light may be anywhere in the electromagnetic spectrum between x-rays and the far infra-red, and the lifetime of the ionized state can be anywhere between one nanosecond and millions of years. The lifetime τ of the ionized state varies exponentially with temperature T as $\tau \propto \exp[E/kT]$. In materials of archaeological interest such as quartz, calcite, feldspar, and flint, E varies between 0.8 electron volts (eV) and 2.0 eV while kT is 0.025 eV at room temperature. Since the argument of the exponential is so large, the lifetime is very strongly influenced by temperature. For example, if $E = 1.8$ eV, the lifetime is three times longer at 10°C than at 15°C, and a state with one million years lifetime at room temperature decays in just seven thousandths of a second at 300°C!

Suppose such a material is heated beyond 300°C for several seconds or more; all the ionized states are discharged. After cooling to room temperature the material will then accumulate ionization from the environment and if the irradiation rate is constant the total energy stored will be proportional to elapsed time. On heating, the amount of thermoluminescent light emitted will therefore be proportional to the age since last firing. This is the principle of thermoluminescence dating. The technique is well established both in archaeology and in earth sciences. Materials in common use provide dates within the range 5 to 500,000 years b.p. for pottery, burnt stone, various forms of calcite, and metallurgical slags.

For successful dating a number of conditions must be met, requiring a very close symbiosis between scientific and archaeological practices. Since the natural dose rate on buried objects is usually dominated by the contribution from nearby (or internal) radioactivity rather than from cosmic rays, it is necessary to determine the site dose rate and mechanism because α, β and γ-rays all have quite different ranges in solids. The constancy of the dose rate is determined by the lifetime of the radioactive material and the accumulation rate depends too on the luminescence lifetime. In some cases daylight is sufficiently energetic and intense to bleach the luminescent centres. At the measurement stage single phase material is usually required, often hand-selected under a microscope from crushed material, and the heating sequence used to release the thermoluminescence is also important. There would be significant advantage if the spectrum of thermoluminescence light could be routinely measured. Whereas that is essential and common practice in solid state physics, only simple filter techniques have so far been widely applied in dating. All these technical features must be taken into account in applying thermoluminescence to dating.

There are other ways in which the trapped electrons can be detected, notably electron spin resonance (ESR), which involves measuring the spectrum of microwave absorption in the sample as the magnetic field is varied. ESR is non-destructive and since heating is not necessary materials such as bone can be studied. A wealth of detailed information is obtained, so much that it can be difficult to detect the age-dependent signals.

Dendrochronology

Quite different lessons are learnt from the history and practice of tree-ring dating. Quantitative application of the method was probably first attempted by A. E. Douglass in the early years of the present century, though the fact that trees grow by adding one ring per year had been realized many centuries earlier (Baillie, 1980; European Science Foundation, 1983). Douglass was interested in the relationship between solar activity and climate, in particular whether the eleven-year and longer period sunspot cycles were paralleled in the earth's climate. Studies based on recently felled trees quickly led to extensive work based on well-preserved ancient wood.

Whereas thermoluminescence dating requires a considerable input from solid state physics, much progress was made in dendrochronology with little or no input from botany or biochemistry. A tree may be thought of as a 'black-box', within each year's environment and weather are incorporated as a thin slice of wood. As Fig. 1 shows, by a process of pattern recognition and ring counting, wood from a variety of sources can be used to construct a continuous chronology. Such chronologies are necessarily either incomplete ('floating') and of only specialist interest and use, or, when continuous, are absolute and accurate to the year. Continuous long-range chronologies have been constructed for Irish oaks (*Quercus robur* and *Quercus petraea*) and bristlecone pines (*Pinus aristata* and *Pinus longaeva*) covering 8000 years or so. The most important ingredient in such studies is the good luck required to find a continuous overlapped set of samples. But the surprising planned result of this archaeological activity has been the absolute calibration of the carbon-dating method, in effect, providing an answer to Douglass' original astronomical question. Serendipity is another characteristic of good science and it is well known that good luck is more often found if one knows where to look for it!

Of course this brief description severely undervalues the scientific basis of the subject which, if the behaviour of different species in different geographical locations is to be interrelated, is very demanding indeed. Pattern recognition too requires sophisticated mathematical and computing techniques. Dendrochronology, though it may be thought of as part of archaeology, is tightly bound into the web-like structure of science with connec-

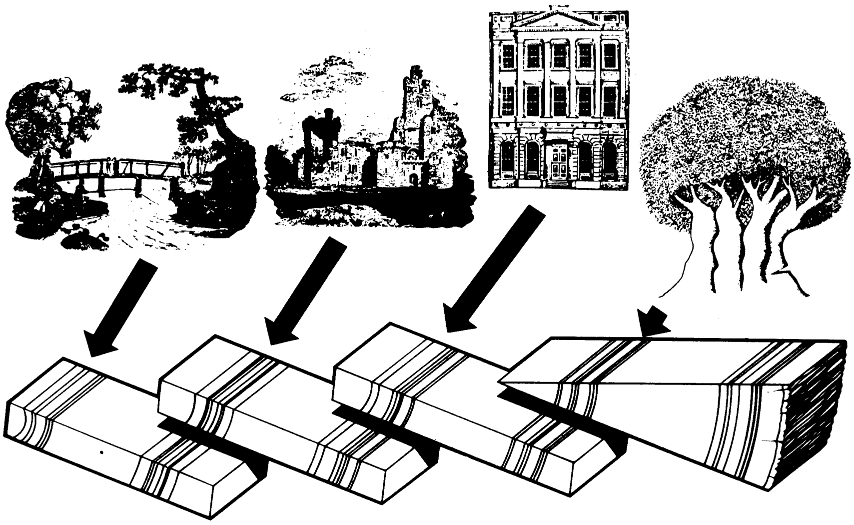

FIG. 1. Schematic diagram illustrating how wood from a variety of sources, but from a single species of tree, can be pattern-matched to form a continuous dendrochronology. (Courtesy, The Ulster Museum)

tions to computational mathematics, biology, geography, climatology, and astrophysics!

Radiocarbon ^{14}C dating

Carbon is present in all organic material, plants and animals. A radioactive isotope of carbon, ^{14}C, is present in the atmosphere in very small amounts (10^{12} times less than the stable isotope, ^{12}C, corresponding to about 60 tonnes distributed throughout the biosphere). It is continuously formed by cosmic ray bombardment of nitrogen. ^{14}C is unstable and decays according to the scheme $^{14}\mathrm{C} \rightarrow {}^{14}\mathrm{N} + \beta^-$ whereon the electron (β^-) can be detected with electronic counters. The nuclear decay rate, dN/dt nuclei per year, is unaffected by terrestrial environmental variations and follows the rule[1]

$$dN/dt = -N/8223$$

or in terms of N_0, the number of ^{14}C atoms present in the

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[1] The decay constant was thought to be 8033 years in the early days of archaeological dating (Libby, 1955; Aitken, 1961), and the value 8223 years (half-life 5700 years: Hall, 1980; Hedges, 1985) is commonly used in present day archaeology. Tables for nuclear physics (Lederer and Shirley, 1978) give the value 8270 years.

beginning when the sample contained the equilibrium ratio of the two carbon isotopes in the atmosphere

$$N = N_0 \exp(-t/8223).$$

N is the present number of ^{14}C atoms in the sample and the time t is measured in years.

A fundamental assumption in radiocarbon dating is that the ^{14}C is homogeneously distributed in the biosphere. This should not be taken to imply that ^{14}C is found only in biological systems since many inorganic forms also exist. For example, carbon dioxide exists in the atmosphere, groundwater, the oceans, and in the arctic and antarctic icecaps, and all have been dated using the ^{14}C method. The advent of nuclear weapons provided a step change in the concentration of ^{14}C in the atmosphere which has been used to demonstrate that, averaged over a decade or so, the biosphere is homogeneously mixed. The second assumption is that the production rate of ^{14}C in the atmosphere has been constant.

Since ^{12}C is stable and accounts for almost all the carbon in once living material, it follows that a measurement of the ration of $^{14}C/^{12}C$ in archaeological material suffices to determine the present^{14}C concentration and hence the material age. This is the principle of ^{14}C radiocarbon dating.

The two long dendrochronologies mentioned earlier were researched in close collaboration with expert radiocarbon dating laboratories. As a result, two independent calibrations of the technique are available. Their manifest internal agreement clearly validates and calibrates the method (which was the primary objective), but much more has been achieved. The two results related to different species, widely separated geographically in very different climates. The assumption of constant ^{14}C creation rate is demonstrated to be unrealistic, leading to errors of about 150 years in apparent age a few hundred years ago, decreasing to zero error at 0 BC and increasing to about 10 per cent or 800 years by 6000 BC. These gross differences between ^{14}C and calendrical age can be avoided by using the calibration curve instead of the decay rate equation, but detailed discussion of the fine detail in the calibration continues.

Accelerator mass spectrometry

From a technological and archaeological viewpoint the low concentration of ^{14}C presents a problem because several grammes of modern carbon are required to produce a count rate of one disintegration per second. Several hours of counting are required for a sufficiently accurate measurement to be made. By contrast the total number of ^{14}C atoms present in such a sample is 2.5×10^{11} (N in the decay equation), and this represents a considerable amplification factor in experiments which determine the number of atoms present (rather than the decay rate). This allows the use of much smaller samples and, potentially, the determination of greater age with greater accuracy.

Mass spectrometers are essentially atomic weighing machines which can separate not only the ninety-two elements but also over 300 isotopes. As there are technical difficulties in unambiguously counting atoms of an isotope with a given mass without simultaneously counting molecules with the same mass, the accelerators required are rather costly. With these machines one can directly count the number of atoms of a particular species which are present.

My final example is of a high risk, expensive but highly successful project. In 1978 the Science-based Archaeology Committee awarded a grant for the construction of an accelerator-based dating system for ^{14}C to the Research Laboratory for Archaeology at Oxford. It is by far the largest investment that the Committee has ever made, amounting to almost half of their available funds for many years and totalling about £1.4 million by 1985. In that year the review panel was able to report that

> the work is of the highest technological and scientific merit, and we have been advised that its achievements to date are comparable with those elsewhere in the world. Its reputation in the ^{14}C community is very high. It has already made a substantial impact on archaeology in the U.K.

The accelerator project is one of the very few examples of the application of second generation techniques in science-based archaeology. Before the use of accelerator mass spectrometry for ^{14}C dating there had been considerable experience and use of the radioactive β-counting technique. It was well established in archaeology, as evidenced by the current estimate that upwards of 50,000 'dates' have so far been obtained (Hedges, 1985, 1987). Many of them have impeccable pedigrees, being linked to independent historical, archaeological, or (for example) dendrochronological sources. In 1978 it was therefore possible to predict with confidence the benefits of the accelerator method. The main advantage of being able to determine the age of samples 1000 times smaller than previously has been realized. I doubt that the confidence which is necessary to create and approve such an expensive project could have existed without the previous decades of work which established the conventional ^{14}C dating method. A facility which is widely acclaimed gives added confidence and its very existence shows that archaeology is able to command resources on a substantial scale where necessary.

There are many conclusions to be drawn from this experiment in funding science in archaeology. I want to concentrate, in the next part of this lecture, on those relevant to the future structure and future funding of science-based archaeology.

The next phase

Research on new instruments and measurement techniques is supported throughout the research council system. Within the SERC Science Board, where science-based archaeology competes for funds with other physical sciences, practice in other subjects has been that the funding of successful innovations is taken over by the originating research group. Newer methods replace older ones, novel techniques create new demands on resources, but may result in commercial instruments and income.

The process has been somewhat slow to develop in archaeology, though in 1984 the Science-based Archaeology Committee did provide a grant specifically to develop and explore the potential of a thermoluminescence dating service to support work on archaeological ceramics. Since the completion of the initial phases of the accelerator-based radiocarbon dating programme at Oxford, about half of the time on this facility has been made available to other institutions. This parallels the practice of other Research Council committees who provide, for example, nuclear magnetic resonance facilities for chemists, high pressure facilities for physicists, and neutron beams for a variety of research disciplines. Research programmes too lead to new techniques and facilities, which researchers from other institutions may use, and the provision of resources to collaborative programmes is a growing practice.

The SERC review panel identified three problems for archaeologists which must be solved if the rate of progress in science-based archaeology is to be maintained during the next few years when competition for support will intensify: the whole community of archaeologists is very diffuse, and different groups are concerned with different objectives and constraints, the organization, structure, and funding of archaeology in universities and polytechnics is that common in arts rather than science departments; and the teaching and career structure which would be necessary for the full integration of some science into archaeology hardly exists.

Although the Council for British Archaeology is composed of representatives of many of the organizations involved in British archaeology and has the specific objective of co-ordinating archaeological policy and practice, it is not in a position to solve the perceived problems in science-based archaeology. Two important steps have been taken by some of the organizations with the strongest financial interest in science-based archaeology listed in Table 2. The British Academy, English Heritage and the Science and Engineering Research Council have jointly funded and appointed the co-ordinator recommended by the review panel. In addition to fulfilling the original objectives, this joint activity could also result in the evolution of common policies and support for further developments in science-based archaeology. A reinvigorated standing committee for professors of archaeology has been active for the last year or so and this is a very welcome development.

The second and third problems are largely the responsibility of the universities and the University Grants Committee insofar as funding is concerned. Clearly there is wide demand for arts-based archaeology undergraduate courses and for graduate training and research with both arts- and science-based approaches, but there is no undergraduate course in archaeology which **requires** even one science subject at A level. In the past much of the science-based archaeological research has been done through informal collaboration between scientists and archaeologists. The present statistical cost centre approach to financial planning by both the University Grants Committee and many vice-chancellors will surely make it more difficult for members of biology, chemistry, physics, or metallurgy departments to justify their work on archaeological problems, and for archaeology departments which teach for an arts degree to obtain the resources required for the practice of experimental sciences. Those archaeological departments which have invested in and developed through grants a science base to their work have done so with great difficulty. As a result, many archaeologists with whom I have discussed the question of introducing a stronger science base have been pessimistic about future possibilities. I believe that opportunities exist now which must be taken soon if lasting developments in science-based archaeology are to be achieved.

The first prerequisite is for a national consensus on the requirement for arts- and science-based undergraduate courses and postgraduate training and research. For the time being we must assume that advice has been or will be given in due course and note that the University Grants Committee is currently reviewing the national provision for several subjects, and that the committee has recently adopted a policy of giving more explicit advice than it used to. For the purpose of discussion, I will assume that some university departments will wish to develop a strong science base and I will then explore what opportunities and advice exist for them to achieve that position.

At the undergraduate level of entry, the question of an A-level science prerequisite will become less sharp, since one benefit of the proposed sixth form core curriculum is that **all** university entrants will have achieved a higher level of understanding in science than **some** university entrants have achieved in the past. This is important since, as the successful programmes which I have described show, the objective must be to integrate some science into archaeological studies and practice, rather than to 'buy in' technology on a customer/contractor basis—*caveat emptor!* There is no single format for university departments but there are many models, all of which lead to the same conclusion about the range and scale of activities which are required.

One extreme would be to create departments able to teach a self-contained science-based undergraduate course. And a model for comparison might be those departments of geography which have a science degree undergraduate course or (probably too extreme) departments of oceanography and geology for which UGC advice has already been given. Another model, that of sequential specialization, would be to regard leadership in professional science-based archaeology as a graduate activity requiring specific postgraduate training, experience and/or research. A department would, in addition to its research programme, for example, run one (or two) masters degree courses designed to convert both science and arts graduates into science-based archaeologists. Models for comparison might be some of the many departments currently running one-year vocational graduate courses in laboratory-based subjects for students with a wide range of first degree experience. Whichever scheme archaeologists require, experience in the subjects mentioned above points clearly to a relationship between scale and long-term viability in experimentally based subjects. The conclusion is not a new one. It is well rumoured, perhapse even partially documented, that the University Grants Committee regards some archaeology departments as if they were science-based. It is clear that no university funds its own archaeology department fully as a science department, since all are either in the arts faculty, or have far fewer support staff than their scientific competitors, or are too small to be viable in the terms of present science reviews.

I have spent enough time on matters relating to the aspirations of scientists in archaeology and on the changes in archaeological education which some would like to see. Let me conclude with a description of two areas which should cause concern. The first, computing in archaeology, illustrates both the problems which arise when new technology is incorporated into weak organizations, and the opportunities which exist for large (but not small) groups in high technology. The second, further developments in accelerator-based mass spectrometry, will review some developments in the United States of America. Comparable facilities are not used in the same way in the United Kingdom.

Computing in archaeology

As in many sciences, the promise of computers was recognized many years ago in archaeology. For example, in a paper to the British Academy in 1972, J. E. Doran, F. R. Hodson and D. G. Kendall, classified computer applications in archaeology within six headings:

(a) descriptive statistics and data organization
(b) classification, scaling, and other methods of multivariate analysis
(c) chronological seriation
(d) data banks
(e) simulation
(f) special purpose studies.

By 1985, when the SERC review panel met, little coherent work had been done in any of these categories but, in spite of rapid developments in computer technology, we saw no reason to reclassify possible applications in archaeology. Without question a number of fascinating achievements could be recorded under (f), for example, in archaeoastronomy and in quantifying wear patterns in prehistoric tools using auto-correlation functions. But too much of the department activity which we saw was well intentioned but was prone to obsolescence.

Many university departments in many disciplines had realized by 1970 the advantages of expensive microcomputers and were well poised to embrace the cheap microprocessor when it arrived in the mid 1970s. However, few could see far enough ahead and many spent scarce resources on promises. Some archaeology departments followed the trend, but at great cost, for they generally lacked the economies of scale which permitted large experimentally based departments to write off their losses. It may well be that those departments which continued to archive their excavations on mainframe computers through five-hole paper tape data loggers (even when I was a student eight-hole was the norm!) have done more archaeology than those which were temporarily distracted by the now incompatible PETS or ACORNS etc. The situation is clearer now.

Most of the computer applications listed in 1972 had a clear data base or large-scale statistical requirement which made the microprocessor approach inappropriate, except for data logging in association with a mainframe computer system. As the power of microcomputers and minicomputers has increased in relation to their cost, a new opportunity has arisen for archaeologists; interactive computer graphics designed for other purposes can help one to visualize and operate upon multi-dimensional excavation archives.

Whether in Disney cartoons, aerospace simulations, or in the study of protein conformations and drug design, large-scale computers are important technological tools. All archaeological sites are multi-dimensional in space and time, and their interpretation usually relies on two-dimensional black on white sections of this space-time, meticulously drawn at great cost. In October 1986 (Ottoway *et al.*, 1986) spectacular results showing minicomputer stereographic colour views of an archaeological site were published (only in flat two-dimensional black and white). The impact of such interpretive computation on well constructed archaeological archives is dramatic, though one must admit that the response of those archaeologists present at the lecture on which this article is based was not enthusiastic at the time.

I believe that the audience's lack of enthusiasm was misplaced and may originate in the widely held view that such facilities are 'too expensive for archaeological aspirations'. In essence we are considering the interactive colour graphics provided by a computer system costing £250,000–£500,000. It is well known in all sciences and in many technologies that the benefits of multi-dimensional imaging colour graphics, stereoscopic imaging, and image processing are enormous. Coupled with human interpretation, intervention, and interactive guidance insights can be achieved which are difficult to justify and quantify a priori. Such benefits would clearly be valuable in many aspects of archaeology. But could the resources be secured?

My answer is 'Yes'; but only with a great deal of effort, and the benefits would extend beyond the boundaries of archaeology into the environmental and earth-sciences. In some respects archaeology lags behind these other subjects in computational activities where considerable use is already made of satellite data and processed images. That is related to my final topic for discussion, but let me continue with the present one. Assume for a moment that the case is proven in principle for advanced image processing and computer graphics in archaeology. How might we proceed? What are the ground rules?

The first rule is that the amount of money requested is not a problem in the absolute sense. In the £500,000 range there are hundreds of projects which have been funded by the five research councils, and dozens have been funded in the last few years as explicit UGC projects. Remember too that each 'New Blood' post carries a life-time salary bill of this magnitude! Lest it be thought that these large grants are not available outside conventional science and technology disciplines, we should remember that the SBAC accelerator-based dating project, which is outstandingly successful, cost more.

The second rule is that not only should the referees concur but that there should be sufficient **informed** demand. That will mainly depend on the establishment of an appropriate leadership and structure for British archaeology. If, for example, an excavation archive format together with interpretive objectives for post-excavation analysis (linking to the pre-excavation objectives, even when 'rescue'-oriented, and to conservation technology) could be agreed across all sections in British archaeology, then the creation of a national centre might be quite straightforward. Some aspects of this format are already in place following national reviews in recent years with the leading organizations. There are many opportunities for collaborative funding in such a project and the cost per archaeologist of such a computer facility would be small. It could be set up in a variety of ways but the important point is that it would require coherent input from all organizations with an interest in archaeology.

Beyond archaeology: opportunities missed in the UK

An assumption of our research council system is that all science research (and more besides) is covered somewhere in the five research councils. One has heard of many complaints over the last twenty years about topics falling between research councils and thereby failing to achieve funding. Replies to these complaints generally follow the line that all borderline cases are referred to both councils and that there are no gaps. In my experience that is true, and officials spend a considerable amount of time negotiating borderline cases. For historical reasons the environmental and earth-sciences are mainly funded through the Natural Environmental Research Council for their research, whereas the science input to archaeology is mainly funded through the Science and Engineering Research Council. This is problematic for the development of all the named subjects, as is the division of medical and biological science between the Science and Engineering Research Council and the Medical Research Council (and, to some extent, the Agriculture and Food Research Council). I take as my final example accelerator-based isotope analysis, excluding ^{14}C. The National Science Foundation in the USA funds all subjects in environmental, earth, and archaeological science, whereas we in the UK split these two subjects between several research councils. In our research council activities we have assets which match in quality those available in the USA, but they are not available to the same communities. Some would say that there is little or no demand, others would claim that access is denied; wherever the truth lies it is clear that opportunities are being missed in this field in the UK.

Accelerator mass spectrometry in the USA

'Particle accelerators, such as those built for research in nuclear physics, can also be used . . . to measure rare isotopes at very low abundance ratios' (Elmore and Phillips, 1987). 'In the past few years, research applications of accelerator mass spectrometry have been concentrated in the earth sciences (climatology, cosmo chemistry, environmental chemistry, geochronology, glaciology, hydrology, igneous petrogenesis, minerals exploration, sedimentology and volcanology). . . . In addition, accelerator mass spectrometry may become an important tool for the materials and biological sciences.'

While many applications of low energy mass spectrometry are funded by several of the research councils, most of the examples listed in Table 4 are not available to earth scientists, environmental scientists, or archaeologists. This situation arises not because the UK is too poor, but because our research funding is compartmentalized with barriers which can be proven to be low by officials but which are perceived to be too high by potential applicants. Rather than debating that issue let us look instead at the opportunities which exist for exciting research in the archaeological, earth, and environmental sciences using existing UK facilities.

Different problems have different time-scales. The 5700 year half-life of ^{10}Be at 1.6 million years is matched to the needs of those who study crystal processes which have that time-scale because beryllium has a high affinity for the clay components of soil and sediment. ^{36}Cl is an ideal isotope for dating and tracing old groundwater and antarctic ice because of its half-life of 300,000 years. Carbon, aluminium, and chlorine have no radioisotopes with half-lives between 1 hour and 1000 years. All are important in biological sciences, and accelerator-based mass spectrometry has sufficient sensitivity for them to be developed as tracers or probes (Elmore and Phillips, 1987). There is no requirement for the isotope to be radioactive and other isotopes are of potential interest. Some are listed in Table 4.

All these isotopes could be studied at the Nuclear Structure Facility at Daresbury but the only substantial programme in the UK uses the ^{14}C accelerator at Oxford. ^{36}Cl is the subject of a feasibility study at Daresbury but there is as yet apparently little demand for such facilities (Lilley, 1986).

The range of research undertaken in the United States is very broad as Table 5 shows. Many of the problems listed have a clear and strong commercial application while others are more fundamental. Perhaps other programmes are more important, but it seems to me that here is an exciting example of a wide-ranging strategic and basic research programme in a variety of disciplines

TABLE 4. *Accelerator mass spectrometry in USA: isotopes*

Radioisotopes	^{10}Be	^{14}C	^{26}Al	^{36}Cl	^{129}I
Half-life (years)	1.6 M	5730	0.7 M	0.3 M	16 M
Stable isotopes	^{9}Be	^{12}C, ^{13}C	^{27}Al	^{35}Cl, ^{37}Cl	^{127}I
Terminal MV	7.3	2	7.5	8	5

Other useful isotopes include ^{32}Si, ^{41}Ca, ^{59}Ni, and ^{60}Fe which are radioactive, and ^{187}Os, Pt, Ir, B, P, and Sb which are stable.

Source: Elmore and Phillips, 1987.

TABLE 5. *Accelerator mass spectrometry in USA: the science programme*

^{10}Be Activities	
Geology	beryllium has a high affinity for clays, hence studies of: manganese nodules marine sedimentation soil erosion sediment incorporation in volcanoes
^{14}C Activities	
Archaeology	dating
Oceanography	life cycle of foraminifera chronology of marine sediments deep sea vent organisms
Organic geochemistry	
Materials science	^{14}C in silicon
^{36}Cl Activities	
Hydrology	aquifer dating tracing using the ^{36}Cl pulse from 1950s' bombs
Climatology	extending the ^{14}C dendrochronology to 1 M years
Several isotopes	
Biological sciences	non-radioactive tracers—C, Al, Cl—are unique having no isotopes with 1 hour to 1000 years half-life
Physics	hunting the quark
Sedimentary systems	polar ice cores ^{10}Be, ^{14}C, ^{36}Cl correlation marine sediments ^{10}Be and geomagnetism
Cosmochemistry	isotopic ratios determine extraterrestrial origin
Dating	cosmic rays imprint ^{10}Be, ^{26}Al, ^{36}Cl in rocks

Source: Elmore and Phillips, 1987.

to which the UK hardly contributes (except in ^{14}C archaeological dating). For once lack of resources seems not to be the main problem since the basic facilities already exist. Could it be that we are handicapped mainly by the thinly spread and overdiversified way in which the research community and funding agencies are arranged?

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