UC Berkeley

Contributions of the Archaeological Research Facility

Title
The Application of the Physical Sciences to Archaeology

Permalink
https://escholarship.org/uc/item/76m8x6fm

Authors
Stross, Fred H.
Morrison, Frank
Perlman, Isadore
et al.

Publication Date
1971-03-01

CONTRIBUTIONS
OF THE
UNIVERSITY OF CALIFORNIA
ARCHAEOLOGICAL RESEARCH FACILITY

Number 12 May, 1971

THE APPLICATION OF THE PHYSICAL SCIENCES TO ARCHAEOLOGY

Edited by **Fred H. Stross**

A symposium held on June 23, 1970 at the University of California, Berkeley, under the auspices of the Pacific Division of the American Association for the Advancement of Science, the California Section of the American Chemical Society, and the San Francisco Society of the Archaeological Institute of America.

This publication has been aided by a grant from the Pacific Division, American Association for the Advancement of Science.

UNIVERSITY OF CALIFORNIA
DEPARTMENT OF ANTHROPOLOGY
BERKELEY, CALIFORNIA

CONTRIBUTIONS
OF THE
UNIVERSITY OF CALIFORNIA
ARCHAEOLOGICAL RESEARCH FACILITY

Number 12 May, 1971

THE APPLICATION OF THE PHYSICAL SCIENCES TO ARCHAEOLOGY

Edited by Fred H. Stross

A symposium held on June 23, 1970 at the University of California, Berkeley, under the auspices of the Pacific Division of the American Association for the Advancement of Science, the California Section of the American Chemical Society, and the San Francisco Society of the Archaeological Institute of America.

This publication has been aided by a grant from the Pacific Division, American Association for the Advancement of Science.

UNIVERSITY OF CALIFORNIA
Department of Anthropology
Berkeley

CONTENTS

THE APPLICATION OF THE PHYSICAL SCIENCES TO ARCHAEOLOGY

I. INTRODUCTION

Fred H. Stross,
Research Associate, Archaeological Research Facility

As a discipline, the History of Science has led an unobtrusive existence for some years. By contrast, a more recent undertaking which we may call Science in History, has become a burgeoning field in the past few decades. The development of analytical instruments with vastly increased sensitivity, precision, and sample throughput, and of a strikingly powerful computer technology has become a great aid in establishing and testing elements of the fabric of history and, perhaps more significantly, of prehistory. To acknowledge these developments, a symposium entitled The Application of the Physical Sciences to Archaeology was organized by the writer for the Pacific Division Meeting of the American Association for the Advancement of Science, by the California Section of the American Chemical Society, with the co-sponsorship of the San Francisco Society of the Archaeological Institute of America. Its immediate purpose was to note and discuss the most recent advances in the field defined by the title of the symposium. It was held on June 23, 1970, in 1 Le Conte Hall on the Berkeley campus of the University of California, and consisted of a morning and an afternoon session and ended with the showing, at the Lowie Museum of Anthropology, of the color film "Neutron Activation of Pottery," which describes the work of the Lawrence Radiation Laboratory in this area.

The symposium was opened by the Vice-Chancellor, Dr. Robert E. Connick, who recalled the role played by this University in the early work on the utilization of carbon 14 especially for dating carbon-containing compounds. The symposium was well attended by an audience predominantly consisting of those seriously interested in the topic. This interest was expressed in the nature and number of questions brought up during the discussion periods. Regrettably, the first lecture scheduled had to be canceled. It was entitled "The Role of Chemistry in Saving the Nubian Monuments, with Special Reference to the Abu Simbel Temples," and was to have been given by Dr. Zaki Iskander, Director General for Technical Affairs, Department of Antiquities, Egypt. At the critical time, Dr. Iskander was called to Venice to take part in a session of conservation experts to help develop plans to forestall the subsidence of that city, which has become a substantial threat during the past few years.

All papers, with the exception of that of Dr. Iskander, are reproduced here, in their full text, or, in the case of those of Drs. Curtis and

Perlman, in the form of abstracts. In the meantime, abstracts of the papers have been published in Science, 171, 831-6, 1971.

It is obviously impossible in a single day to provide a technical summarization of the status of the entire field. The following paragraphs are intended to supplement the proceedings at the meeting and at least to indicate some of the areas in which novel and promising work is being done, and what types of instruments are being used in this work.

It may be worth stressing that the new technology is serving not only the needs of archaeological research per se, but also related needs, including the conservation of the artifacts that are so often the objectives of our studies. The instruments used in both areas, archaeological research, and conservation, often are the same. It may, for example, be of interest to the archaeologist and the art historian to have at his disposal methods for elemental analysis of very small samples of paint pigments - as in the case of the mysterious Maya Blue - and similarly to the restorer-conservator, who might want to make his restoration as inconspicuously as possible. Consequently we may find that an advanced museum laboratory allocates the time available for utilization of expensive analytical instruments to research and day-to-day problems in conservation in a ratio of 2:3, respectively. For convenience, one may still group the activities into inorganic-physical and organic-chemical, although the specialized areas of today do not fall into these classical categories.

The most widely used operation in the first group probably is the elemental analysis of the material at hand. Many techniques are available, varying in first cost, cost per analysis, sensitivity, precision, expertise required, and complexity of ancillary facilities. One of the most versatile and promising instruments is the spark source mass spectrometer. With it, essentially all elements can be determined with very high sensitivity. The sample requirements are usually very small. The operation of the instrument can be taught to a skilled non-professional technician, but the supervision and interpretation especially of non-routine samples must be performed by a professional physicist-chemist with the necessary background. The spark-volatilized proportion of the sample that reaches the analyzing section of the instrument is very small, so that even a small sample must be thoroughly mixed to give representative results. Moreover, because of the extreme sensitivity of the method, fastidious housekeeping is necessary to avoid contamination, which easily causes erratic results. The cost of an installation ranges between $100,000 and $150,000.

X-ray fluorescence spectrometry is a very popular technique for elemental analysis because of its relative simplicity and the short time required for analysis in some circumstances. Depending on the accessories available (and the corresponding investment), it is relatively easy to determine, in many cases quite sensitively, most elements present, starting with aluminum (atomic number 13). To achieve good precision and to convert the output into absolute units when using different materials, however, careful work and a fair investment in analytical time are necessary. The sample size can vary only within relatively narrow limits (roughly of the size range of coins or buttons), except for specially designed equipment. The analyzing beam penetrates only on the order of microns, and the surface of the sample to be analyzed must therefore be representative of what is desired in the analysis. That is to say, if the analysis is to reflect the composition of the bulk of the material, the surface must be representative of the bulk. If, on the other hand, one wishes to analyze the surface, as distinguished from the bulk, of the sample (e.g. to determine surface enrichment), x-ray fluorescence is the method of choice, followed, for instance, by neutron activation analysis to obtain bulk composition. Equipment ranges from $20,000 up. Many variants of the technique are also available, such as the gamma ray spectrometry developed at the U.C. Lawrence Radiation Laboratory, the electron microprobe, and others.

The optical emission spectrometer has been much used for elemental analysis in archaeology, for example by Cann and Renfrew in their studies of Mediterraean and Near Eastern obsidian. Getting accurate results is a laborious process. When using this technique, the sample is destroyed, while x-ray fluorescence and neutron activation in principle are non-destructive, although special objectives may make destruction of the sample necessary.

The electron scanning microscope also shows promising new developments. This technique is particularly attractive in that it can be combined with non-dispersive x-ray spectrometry and then permits correlation of shape with composition, and presents a three-dimensional view of the object - but on a minute scale. A typical field of scan is on the order of 1000 Angstrom units, which may be both an advantage and a disadvantage. The price at present ranges upward of $50,000, but there are designs for production at a substantially reduced cost.

Neutron activation analysis is another attractive technique for elemental analysis. Even more than in the case of the other techniques, we pay for what we get. Small instruments useful for the determination of only a few elements can be installed for as little as $50,000. The large reactors that have been used for pioneering and most informative analyses of ancient glass, pottery, coins, and other metal objects, etc., have mostly been government installations, essentially accessible only to the personnel permanently associated with it. Occasionally outsiders may obtain analyses through personal acquaintance or on a commercial basis. The excellent results obtainable by means of such installations are recorded in the work of Sayre, Perlman and Asaro, Gordus, and others in the U.S., and of their European counterparts. To take advantage of the capabilities of neutron activation analysis, such standard but expensive instruments as multichannel analyzers, and sophisticated computer services should be available. The installations can determine upwards of 30 (as high as 50) elements with varying, but often very high, sensitivities and precision. The reactors can handle very large samples, if required, and the analytical results are good averages of the concentration of each of the elements over the whole sample.

Other techniques are also available, such as atomic spectroscopy, emission spectroscopy, and the classical wet chemistry. Under special conditions these may still be effective, and in the hands of skilled analysts can give excellent results. For laboratories planning new installations, however, the techniques indicated further above will probably be more attractive.

Among the many problems for which elemental analysis has been used during the past years, the determination of minor- and trace-element patterns of composition of obsidian has been of significance. Assuming relative homogeneity of individual lava flows and diversity between the flows, one can, by sensitive analysis of source samples and artifacts, in many cases establish correlation between an archaeological site at which the obsidian was found, and its volcanic source. Such studies have been made for Mediterranean regions and the Middle East, and for substantial sections of North and Central America. Thus it has been concluded that some desirable varieties of obsidian in Mexico and Central America were traded as far as about one thousand miles as early as in Middle-, and possibly Early Preclassic times.

In the inorganic-physical category there are also interesting developments in the thermoluminescent method for establishing the date of the last firing of ceramic materials. Continued work on the method during the past few years, reported in this symposium, have made this method quite reliable, if the "archaeological" and the maximum "spurious" age are not too close together. It appears now that recent work in the Conservation Center of the Los Angeles County Museum promises to make the determinations both simpler and more dependable.

In the organic-chemical field there also has been considerable progress. Asphalts, resins, varnishes, solvents, are only a few of the multitude of substances that have been subjected to such experimentation. Amber has been studied by infrared analysis quite extensively during the past few years. Gaschromatography, and pyrolysis-gas chromatography are used, but probably more in the service of conservation than in archaeological research. Such complex installations as gas chromatography - high resolution mass spectrometers (price in the $100,000 range), which can not only separate organic mixtures into their component groups, but also identify these components, are justifiable only where there are continued demands for this kind of analysis. Less elaborate techniques, such as thin-layer, and paper chromatography, for which equipment is available in the few-hundred to few-thousand dollar range, are very serviceable in the hands of a skilled chromatographer, where rapid mass production of analyses is not a prime requirement. One must bear in mind, of course, that gas chromatography is concerned with volatilizable substances, while the liquid chromatographic methods indicated are used to analyze liquid and soluble materials. There is a large overlap, but not complete identity in these substances, and to a certain extent these techniques can be considered complementary rather than interchangeable.

After the presentation of the papers, Dr. Albert B. Elsasser conducted the participants of the symposium on a tour of an exhibition entitled Science and Archaeology, organized by himself and the writer, and shown at the R. H. Lowie Museum of Anthropology at the University of California at Berkeley from November 1969 on, which was held over especially for the symposium that is the subject of this publication. The topics of the individual exhibits were: Authentication of Antiquities; Cosmic Rays through the Pyramids; The Magnetometer; Rapid Chemical Analysis by X-Ray Fluorescence (including a working instrument operating at the exhibition); Element Analysis of Obsidian; Prehistoric Human Coprolites; Reconstruction of an Ancient Plastic Art; Obsidian Hydration Dating; Radiocarbon Dating; Potassium-Argon Dating; Thermoluminescent Measurement; Nuclear Fingerprinting of Ancient Pottery*). The exhibition, arranged with a particular eye toward stimulating interest in interdisciplinary studies, was much frequented by academic study groups, including many secondary school classes. After the Exhibition closed in Berkeley, it was shown on the university campuses at Riverside and Scripps College at Claremont, California.

---

* Contributors were L. W. Alvarez, F. Asaro, C. R. Berger, H. R. Bowman, G. H. Curtis, A. B. Elsasser, R. D. Giauque, R. F. Heizer, W. F. Libby, H. F. Morrison, L. K. Napton, I. Perlman, R. J. Rodden, F. H. Stross, R. E. Taylor, from several campuses of the University of California; J. V. Noble, from the Metropolitan Museum of Art, New York, D. P. Stevenson and J. R. Weaver (retired), from Shell Development Company, Emeryville, California.

II. HIGH SENSITIVITY MAGNETOMETERS IN ARCHAEOLOGICAL EXPLORATION

H. F. Morrison

Department of Engineering Geoscience
University of California, Berkeley

Surveys of archaeological sites with compact, portable, magnetometers have been increasing in popularity as archaeologists come to realize the power of this technique in detecting and delineating subsurface features. From their original use in locating Roman kilns in Britain, magnetometers are now used in virtually all phases of archaeological exploration, from mapping city plans to studying differences in soil profiles between archaeological and non-archaeological sites. In this brief review we will present some of the applications of the newer high-sensitivity magnetometers.

The basic principle of the magnetic method of geophysical exploration is that inhomogeneities in magnetic properties of the ground cause departures from the normal configuration of the permanent magnetic field of the Earth. If these anomalies in the magnetic field can be detected in measurements made over the surface of the ground, using a magnetometer, their characteristics may be used to deduce the nature of this inhomogeneity. It is important to realize that with this technique no energy is transmitted or injected into the ground by the surveyor. The method is a passive one in which the magnetometer simply measures fields which are present all the time and which are properties of the subsurface features.

Two basic magnetic properties are involved in the study of magnetic anomalies. The first is ferromagnetic susceptibility, that property of certain metals, alloys, and minerals to assume a magnetization in the presence of an inducing magnetic field. This induced magnetization in turn results in a secondary magnetic field and it is this field that produces the anomaly that is measured at some point exterior to the region of high susceptibility. Other types of magnetic susceptibility exist (e.g. paramagnetic and diamagnetic) but the susceptibility is so low that the resulting geophysical anomalies are not presently measurable. With the rocks or dressed stone used in construction there is usually a sufficient contrast in ferromagnetic susceptibility with the enclosing soil to produce a measurable anomaly.

The second property is that of natural remanent magnetization. Certain minerals may possess a large natural magnetization, acquired through some process early in their history, which produces a field or anomaly that is independent of the inducing field. For many years magnetic field exploration was carried out, and the results interpreted, on the assumption that the majority of anomalies were of the induced type. Recently, however, geophysicists have realized that remanent magnetization predominates in many cases and in particular Aitken (1961) has shown that important archaeological anomalies are also of this type. Features of archaeological interest that possess large remanent magnetization are fired bricks and tile, kilns, and hearths.

The success of conventional magnetic surveying in the search for mineral deposits is well documented and presentations of these techniques are to be found in standard texts such as Dobrin (1960), Grant and West (1965), and Jakosky (1950).

These surveys have used either balance magnetometers (ground surveying only) with a maximum sensitivity of about 5 gammas (γ) (1 gamma = 10^{-5} oersted; the earth's normal field is approximately 0.5 oersted), or fluxgate magnetometers with a maximum sensitivity of about 5 γ. Both these devices measure the magnetic field in component directions. The introduction of the proton magnetometer (Packard and Varian, 1954; Waters and Francis, 1958) signalled the era of high sensitivity total field magnetometers. The proton magnetometer has a maximum practical sensitivity of 0.1γ and its simplicity, light weight, and minimal associated read-out electronics have made it a particularly suitable device for rapid ground surveying. Aitken (1960) has summarized the principles of operation and the applications of proton magnetometers in archaeology. Alkali vapor magnetometers (Bloom, 1962) while retaining much of the operational efficiency of the proton magnetometer, have sensitivities as high as .003γ and have opened up a whole new technology in magnetic exploration. Review articles on the applications of these new magnetometers have been presented by Breiner (1965), Langan (1966), Hood (1966), Rover (1967), and Giret and Malnar (1965). We will discuss briefly below the operating principles and modes of field operation and then discuss in detail the applications of interest to this review.

The alkali vapor magnetometers work on the principle of optical pumping. The commonest varieties use cesium or rubidium although units have been designed using potassium, sodium, or metastable helium. We will consider the rubidium magnetometer for this simplified discussion. Light emitted from incandescent Rb^{85} is filtered to pass the spectral line at 7947 A. This light is passed through a cell containing Rb^{85} vapor and the transparency of this cell is a function of the amount of energy absorbed from the light to pump electrons in the Rb^{85} atoms up to higher energy levels. Eventually (a time measured in micro-seconds) the upper energy levels are filled and cell becomes transparent. This pumped, excited state can be disrupted if a weak, high-frequency magnetic field is applied to the cell. Especially if a frequency equal to the precession frequency of the electrons undergoing transition is applied, the disruption of the pumping effect is particularly effective and the cell becomes opaque to the light source. The effectiveness of the observation, however, is critically dependent on the ambient magnetic field and therefore can be used as a sensitive measure of the magnetic field in the immediate vicinity.

A simple magnetometer would then consist of the above cell with a photocell monitor and a variable frequency oscillator. Repeated pumping and monitoring of the frequency which decreases the transparency of the cell would yield sampled measurements of the magnetic field. In practice a self-oscillator principle is employed in which the photocell output is fed back, suitably phase shifted to the coil supplying the radio frequency. This system becomes self-oscillating at the resonance frequency and monitoring of this signal provides a continuous measure of the magnetic field strength. The theoretical sensitivity of this device (Bloom 1962) is estimated to be on the order of $.003\gamma$ and in practice sensitivities of $.01\gamma$ are relatively easy to obtain. Actual field measurement may be made with either a counter (count of number of cycles in a fixed time to determine the frequency) or with a discrimator device that in effect measures the period of the resonance oscillations. This latter approach provides continuous output while the former will only provide a field value at the end of each counting period. The electronics associated with such a magnetometer are simple. Power is supplied to the sensor unit via cable and the signal frequency is returned on the same cable for measurement. Portable instruments have been described by Breiner (1965) and by Ralph, Morrison and O'Brien (1968), and Morrison et al (1970, 1970a).

The disadvantages of the alkali vapor magnetometers are that they are sensitive to the orientation of the vapor cell with respect to the direction of the earth's magnetic field and that they cannot function in regions of high field gradient. The self-resonating oscillation discussed above occurs if the angle between the magnetic field and the light beam through the gas cell is approximately 45° (Bell and Bloom 1957). The effective working angle for the cesium cell is about 30° from the optimum, 45°, and for rubidium it is less. For rubidium this orientation sensitivity can be as high as 0.1γ per degree for a single cell sensor. This difficulty is easily overcome in any application where the sensors can be rigidly mounted or transported with a mounting that maintains constant orientation. A further inherent difficulty is that the magnetic field must be uniform across the vapor cell for the output frequency to be a linear function of field strength. Thus, measured values taken in regions of high field gradient (close to highly magnetized bodies for example) will not be meaningful.

Obviously the first advantage of a higher sensitivity magnetometer is that it can detect smaller anomalies. Unfortunately the increased sensitivity brings with it the problem of low-frequency natural variations in the earth's magnetic field. These fields, called micropulsations, cover a wide period range from diurnal to 0.1 seconds and arise from a multitude of sources in the ionosphere and above. In amplitude they range from hundreds of gammas during magnetic storms to several gammas for normal 100-second period oscillations and down to milligammas for activity around one second period. The larger variations have always been a problem in traditional surveying and it has usually been the practice to have a continuously recording base station to monitor the field and thus prevent the interpretation of a time variation in the data as a spatial anomaly. In periods of high magnetic activity the data are not used. Elaborate techniques of reoccupying a base station at regular time intervals are also used to correct for time variations, but at higher sensitivities, where the micropulsations are more or less continuous, the problem is not so easily solved.

The difficulty may be overcome in two ways, each using two magnetometers. In the first, if the survey area is not too large, use of a base station connected to the roving field instrument so that the difference in field is recorded, provides a satisfactory mapping free from time variations. There is in this method an implicit assumption that the time varying fields are uniform over the area of interest. Micropulsation studies indicate that these fields are uniform at least over distances of 50 or 100 km.

The second method is to use the two magnetometers, closely spaced on a rigid mounting, to measure the gradient of the magnetic field. For small surveys such as are commonly conducted in archaeology both these methods have been used. Aitken (1960), Aitken and Tite (1969), and Mudie (1962) describe the use of proton gradient magnetometers and Scollar (1963) describes a proton difference magnetometer. The highest sensitivity surveys have been conducted using two alkali vapor sensors and these surveys are reported by Breiner (1965), Ralph et al (1968) and Morrison et al (1970, 1970a).

It should be noted that there is no new or better information in the magnetic gradient data compared to the total field data. It is a property of the potential fields being studied that if the field is known over a plane, it can be continued, or calculated, at any higher plane, and this process would also allow us to calculate the vertical derivative from the total field data. However, if the data over the plane are subject to error (time variations, errors in position and of course a basic sampling problem) then the calculated derivative is also in error. Since this derivative has certain advantages for interpretation in that the broad unwanted regional anomalies are suppressed and the resolution of local anomalies is increased (Hood, 1965; Slack et al, 1967), it seems evident that direct measurement of the vertical derivative would be highly desirable. There is a further practical advantage and that concerns the ease of data acquisition and processing. Since the time variations are cancelled in such an array no corrections have to be made in the data, profiles do not have to be 'tied' to compensate for time variations, and the frequency output of the device is ideally suited to digital recording. In addition, the gradiometer has an essentially zero base reading so there is no need to remove regional trends -- a common problem in total field surveys. These latter practical advantages are also present with the difference magnetometer array. A complete study of the field procedures, instrument requirements and sensitivities obtainable with the difference magnetometer array is presented by Morrison et al (1970a).

The field survey usually consists in laying out a rectangular grid on the surface of the ground and the magnetometer readings are taken at the intersection of grid lines. The data are normally recorded in a field notebook or on gridded paper, and later plotted to scale and contoured with lines of equal magnetic intensity. Highly sophisticated methods of automatic digital recording of the field data have been described by Scollar and Kruckeberg (1966). Acquiring the data in digital form has the advantage that all the contouring can be done by the computer and the resulting magnetic maps are likely to be more accurate and certainly easier and faster to produce. In addition, data interpreting techniques such as filtering of the data to reveal certain sought-after features are easily carried out (Scollar 1968).

It is usually evident from the contoured field data where the striking anomalies are located and also whether the data possess any patterns that might be related to street plans, building, drainage tiles, etc. Often this much information is all that the archaeologist requires. The magnetic map pinpoints certain areas of interest where excavation is likely to yield fruitful results or the map indicates in which directions existing excavations should be extended.

If a more detailed interpretation of the data is required, recourse is had to the comparison of the field data with theoretical anomalies calculated for hypothetical subsurface bodies. By a trial and error fitting procedure a model is finally selected which best corresponds to the observed data. The model calculations are usually carried out on a computer and the techniques used in these calculations are described by Heirtzler et al (1962) for two-dimensional features and by Bhattacharyya (1964) for three-dimensional rectangular bodies.

The use of the high-sensitivity alkali-vapor magnetometer is not always warranted. For many cases the proton magnetometer, used singly with some simple corrections for diurnal variations, is adequate for archaeological surveys. While the greater sensitivity of the alkali vapor magnetometer would seem to imply a greater ability to detect subtle changes in susceptibility or to reveal deeply buried features there is a practical limitation that is caused by near-surface magnetic effects. Le Borgne (1955, 1960, 1960a), Aitken (1961), Cook and Carts (1962), and Scollar (1966) have all reported on the anomalously high values of magnetization occurring in soils. This effect is apparently caused by organic action on iron minerals and the result is that the soil assumes a remanent magnetization larger than the magnetization of the parent rock. If this soil layer is broken up, plowed or otherwise rendered non-uniform, anomalies of the same order as, or greater than the anomaly anticipated from the deeply buried feature can result. The desired anomaly is thus obscured in noise and an increase in sensitivity will be of no use.

Scollar (1966) has noticed the interesting effect that in undisturbed soil the various soil horizons may be distinguished on the basis of their magnetization and that archaeological horizons might be detected in vertical section magnetic surveys.

In favorable circumstances, however, the high-sensitivity instruments can be used with spectacular success. The first application was in the search for Sybaris in Southern Italy (Ralph 1964, Breiner 1965, Rainey and Ralph 1966 and Ralph _et al_ 1968). Initial surveys with a proton magnetometer detected a massive brick Roman wall that excavation revealed was built on an older, stone, Greek wall. It was realized that the proton magnetometer would be unable to detect features at the depth of the Greek wall (4 to 5 meters) so that greater sensitivity would be required. Using a difference magnetometer with a sensitivity of approximately 0.05γ it was possible to map magnetic anomalies with a 1γ contour interval. In several locations this procedure located buried roof tiles at depths of 4 meters when the total anomaly was only 3 to 4γ (Fig. 1). Further, the extension of the Greek wall was mapped and quantitative interpretations were made on the depth and the susceptibility of the wall material (Figs. 2 and 3). The soil conditions on the Plain of Sybaris were perfect for a magnetometer survey, there being virtually no surface magnetic noise over much of the area. A similar situation was found at the site of ancient Elis, Greece (MASCA Newsletter 1968). The difference magnetometer here yielded a large portion of the city plan and traced walls at depths up to 4 to 5 meters.

On the other hand, the high sensitivity was found to be unnecessary in a survey conducted on the LaVenta pyramid in Mexico. Originally the difference magnetometer was planned in order to detect the small anomalies that would be associated with basalt structures at the base and center of the pyramid. An unexpectedly high soil magnetization reduced the effective sensitivity to about one gamma but fortunately a large 20 to 30γ anomaly was detected indicating a relatively large structure close to the surface (Fig. 4) (Morrison _et al_ 1970).

In summary, the high sensitivity magnetometers have become practical aids to the archaeologist in finding and delineating subtle subsurface features. They are unfortunately expensive and consequently some care should be taken in advance to determine the magnetic properties of the site to be surveyed. Often soil samples are available from previous excavations and these can be tested in the laboratory with a susceptibility meter. If samples representative of the near surface soils are not available, instruments are manufactured which measure the magnetic susceptibility in situ.

The cost of a high-sensitivity magnetometer survey can vary so much that it would be unwise to quote dollar figures in a review paper of this nature. In many cases established archaeological research facilities may be interested in conducting surveys on a cost sharing basis. The Applied Science Center for Archaeology of the University Museum, University of Pennsylvania under the direction of Miss Elizabeth Ralph, has conducted a wide variety of magnetometer surveys and this group has a wealth of experience upon which to base survey plans for a new site. The Laboratory of the Rheinisches Landesmuseum, Bonn, under the direction of Dr. Irwin Scollar, has also conducted a large number of surveys and this group has indicated that arrangements can be made for processing and interpreting field data. The author has participated in archaeological surveys in Italy, Greece and Mexico and in certain cases could advise on the best survey method. Inquiries should be addressed in care of the author, Engineering Geoscience, University of California, Berkeley.

Assuming that a high-sensitivity survey is contemplated, soil samples should be tested for their magnetic susceptibility. Portable magnetic susceptibility bridges that will accept soil, rock chips, powder, and drill cores are available from Geophysical Instrument and Supply Co., 900 Broadway, Denver, Colorado 80203 and from Bison Instruments Inc., 3401 48th Ave. N. Minneapolis, Minnesota 55429. An in situ coil system is available from Bison that allows one to estimate soil susceptibility by simply placing a coil on the ground.

The alkali vapor sensors themselves are manufactured solely by Varian Associates, Palo Alto, California, and are available on a lease or purchase basis. Inquiries should be addressed to the Geophysical Products Group, Analytical Instruments Division. Those interested in carrying out a difference magnetometer survey should give some attention to the field system utilizing a simple digital counter and portable generator reported by Morrison *et al* 1970a. This system requires that the sensors alone be leased, the rest of the equipment being readily available in an electroncis laboratory.

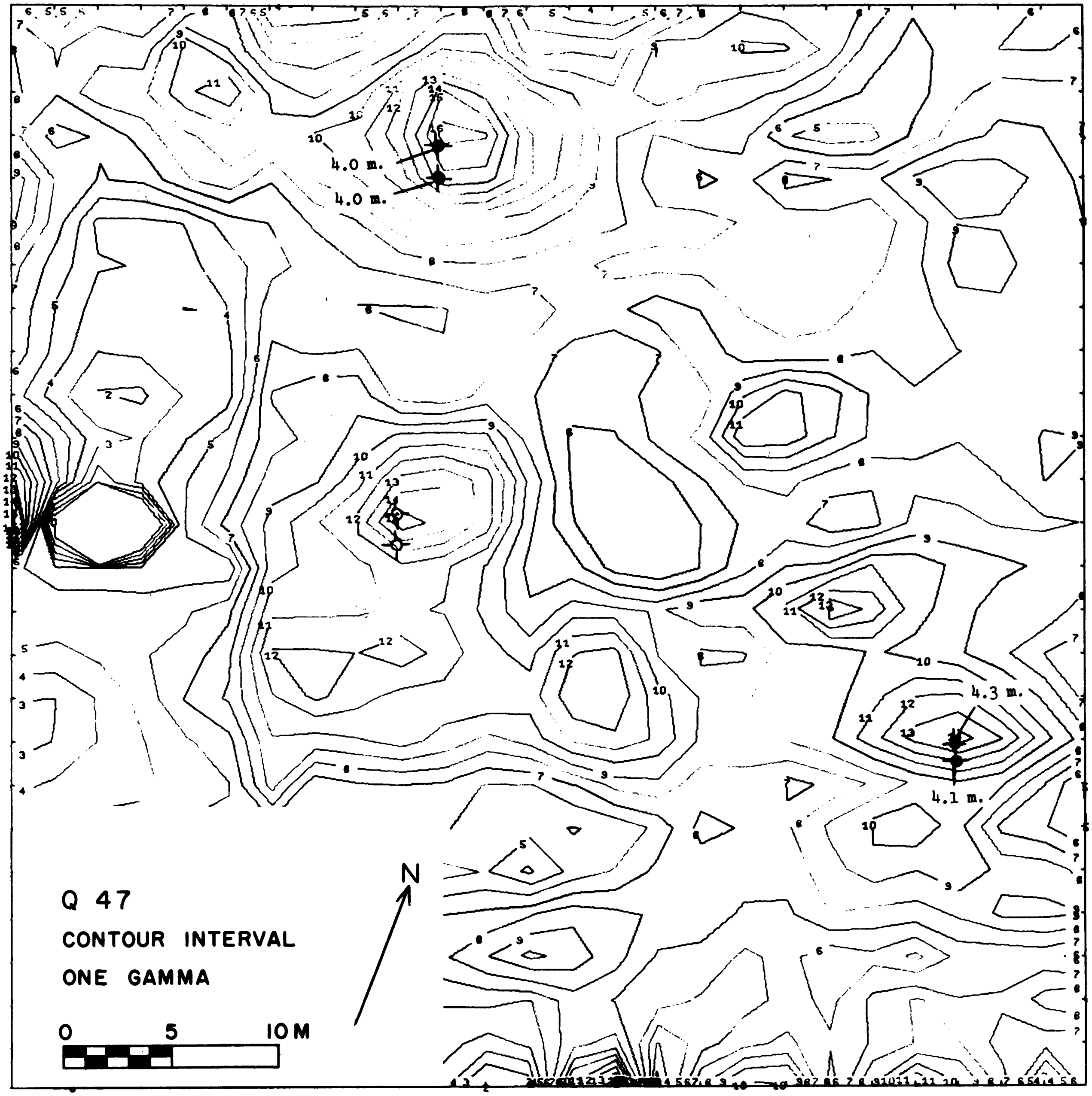


Fig. 1. Computer drawn contours for difference magnetometer survey, Sybaris. Data taken on two meter grid interval. Solid black circles indicate location of drill hole and accompanying number gives the depth to the causative body (in this case fired roof tile). From Ralph et al 1968.

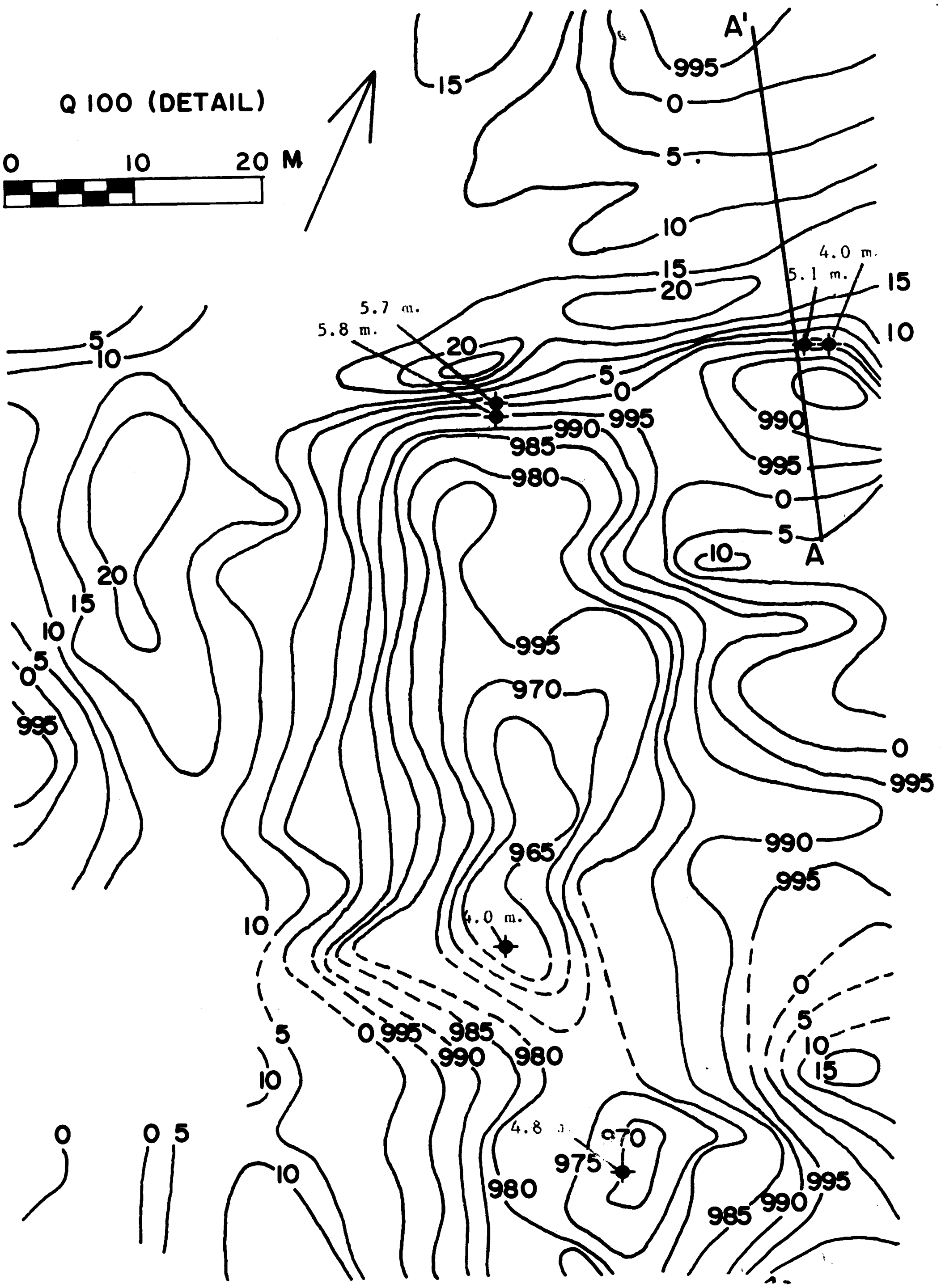


Fig. 2. Hand contoured field data. (Readings are the last three digits of 79,000 and 80,000, i.e. 5 is actually 80,005 arbitrary instrument readings.) The contour interval is approximately 2.5γ and the contour map is inverted - numbers less than 80,000 are positive and those greater are negative. Solid black circles indicate drill locations and the numbers indicate the depth at which stone (wall) was encountered. (From Ralph et al 1968).

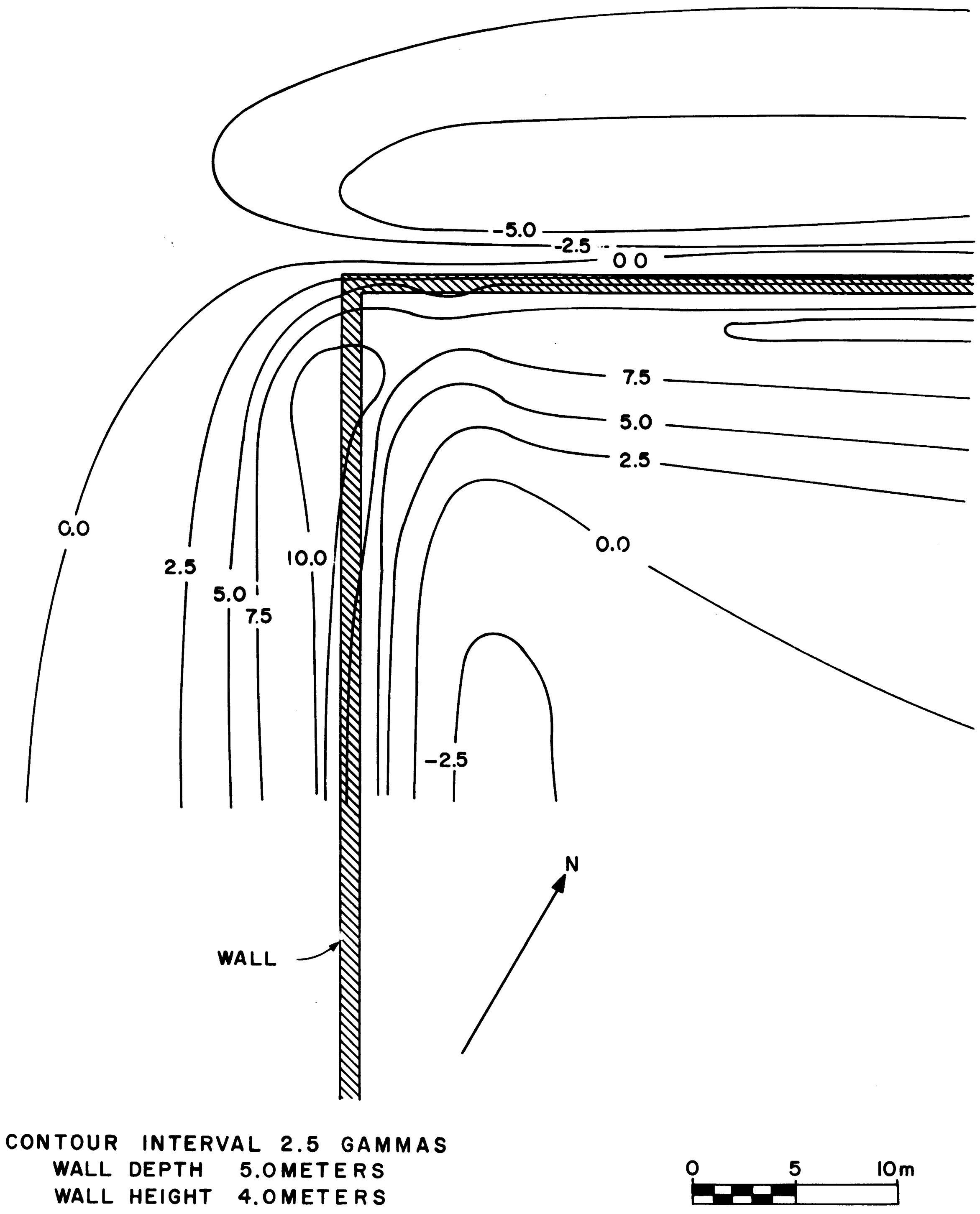


Fig. 3. Computer calculated wall model adjusted to give a good fit to the data of figure 2. (From Ralph _et al_ 1968).

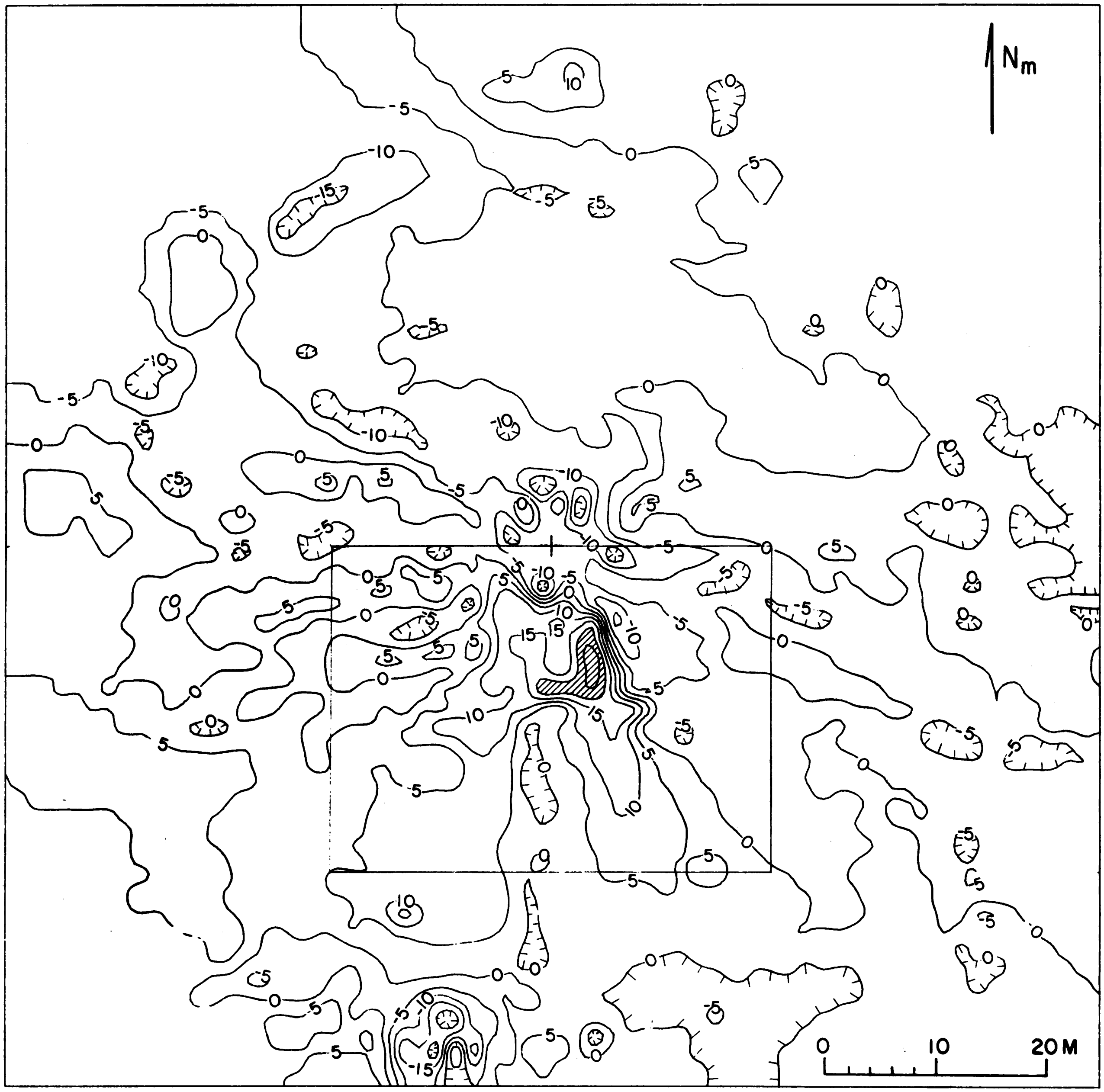


Fig. 4. Computer drawn contours for difference magnetometer survey, La Venta. Data taken at 2 meter intervals along radial lines. Contour interval; 5 gammas. The base of the pyramid is roughly circular and reaches to the margins of the figure. The main anomaly detected is shown in the inner rectangular area. (From Morrison et al 1970).

BIBLIOGRAPHY

1. Aitken, M. J., 1958, Magnetic prospecting I, Archaeometry, v. 1, pp. 24-26.

2. Aitken, J. J., 1958, Magnetic prospecting II, Archaeometry, v. 2, pp. 32-36.

3. Aitken, M. J., 1958, Magnetic prospecting IV, The proton magnetometer, Archaeometry, v. 2, pp. 40-42.

4. Aitken, M. J., 1960, Magnetic prospecting: The proton gradiometer, Archaeometry, v. 3, pp. 38-40.

5. Aitken, M. J., 1961, Physics and Archaeology, Interscience Publishers, Inc., New York.

6. Aitken, M. J., and M. S. Tite, 1962, A gradient magnetometer, using proton free precession, J. Sci. Instrum., v. 39, pp. 625-629.

7. Alldred, J. C., 1964, A fluxgate gradiometer for archaeological surveying, Archaeometry, v. 7, pp. 14-19.

8. Belshe, J. C., 1956, Recent magnetic investigations at Cambridge University, Advances in Physics, v. 6, pp. 192-193.

9. Bell, W. E., and A. L. Bloom, 1957, Optical detection of magnetic resonance in alkali metal vapor, Phys. Rev., v. 107, pp. 1559-1565.

10. Bhattacharyya, B. K., 1964, Magnetic anomalies due to prism-shaped bodies with arbitrary polarization, Geophysics, v. 29, pp. 517-531.

11. Bloom, A. L., 1962, Principles of operation of the rubidium vapor magnetometer, Applied Optics, v. 1, pp. 61-68.

12. Breiner, Sheldon, 1965, The Rubidium magnetometer in archaeological exploration, Science, v. 150, pp. 185-193.

13. Bucha, V., 1967, Intensity of the Earth's magnetic field during archaeological times in Czechoslovakia, Archaeometry, v. 10, pp. 12-22.

14. Colani, C. and M. J. Aitken, 1966, Utilization of magnetic viscosity effects in soils for archaeological prospection, Nature, v. 212, pp. 1446-1447.

15. Cook, J. C. and S. L. Carts, 1962, Magnetic effect and properties of typical topsoils, Jour. Geophys. Research, v. 67, pp. 815-828.

16. Dobrin, M. B., 1960, Introduction to geophysical prospecting, 2nd Ed., McGraw Hill, New York.

17. Fowler, P. J., 1958, Magnetic prospecting III, An archaeological note about Madmarston, Archaeometry, v. 1, pp. 37-39.

18. Giret, R., L. Mainar, 1965, Un noveau magnetometre aerien. Le magnetometre a vapeur de caesium, Geoph. Prosp. v. 13, June.

19. Grant, F. S. and A. F. West, 1965, Interpretation theory in applied geophysics, McGraw Hill, New York.

20. Hall, E. T., 1966, Use of proton magnetometer in underwater archaeology. Archaeometry, v. 9.

21. Heirtzler, J. R., A. Peter, M. Talwani and E. G. Zurflueh, 1962, Magnetic anomalies caused by two dimensional structure: Their computation by digital computers and their interpretation, Tech. Rept. No. 6, CU-6-62-Nonr-Geology. Lamont Geological Observatory, Columbia University, Palisades, New York.

22. Hood, Peter, 1966, A renaissance in magnetic methods of prospecting, Contributions to geological exploration in Canada, Can. Geological Survey Paper, 66-42, pp. 15-21.

23. Hood, Peter, 1965, Gradient measurements in aeromagnetic surveying, Geophysics, v. 30, pp. 891-902.

24. Jakosky, J. J., 1950, Exploration Geophysics, Toija Publ. Co., Los Angeles.

25. Langan, Lee, 1966, A survey of high resolution geomagnetics, Geophysical prospecting, v. XIV, p. 487.

26. LeBorgne, E., 1960, Influence du feu sur les propriétés magnétiques du sol et sur celles du schiste et du granite, Annales de Geophysique, v. 16, pp. 159-196.

27. LeBorgne, E., 1960, Étude expérimentale du trainage magnetique dans le cas d'un ensemble de grains magnétiques très fins dispersés dans une substance non-magnétique, Annales de Geophysique, v. 16, pp. 445-494.

28. LeBorgne, E., 1955, Susceptibilité magnétique anormale du sol superficiel, Ann. Geophysique, v. 11, pp. 399-419.

29. Lerici, C. M., 1961, Archaeological surveys with the proton magnetometer in Italy, Archaeometry, v. 4, pp. 76-82.

30. Linnington, R. E., 1966, An extension to the use of simplified anomalies in magnetic surveying, Archaeometry, v. 9, p. 51.

31. Linnington, R. E., 1964, The use of simplified anomalies in magnetic surveying, Archaeometry, v. 7, pp. 3-13.

32. MASCA Newsletter, v. 3, 1967, Susceptibility prospecting and analysis University Museum, University of Pennsylvania.

33. MASCA Newsletter, v. 4, 1968, Cesium Magnetometer Survey, Ellis Greece, University Museum, University of Pennsylvania.

34. MASCA Newsletter, v. 4, 1968, New cesium magnetometer used in survey at San Lorenzo Olmec site in Mexico, University Museum, University of Pennsylvania.

35. MASCA Newsletter, v. 5, 1969, Cesium magnetometer survey, San Lorenzo Mexico, University Museum, University of Pennsylvania.

36. Morrison, Frank; José Benavente, C. W. Clewlow and R. F. Heizer, 1970, Magnetometer evidence of a structure within the La Venta Pyramid. Science 167, pp. 1488-1490.

36a. Morrison, F., C. W. Clewlow, Jr., and R. F. Heizer, 1970a, Magnetometer survey of the La Venta pyramid, 1969. Contributions of the Univ. of Calif. Arch. Research Facility. No. 8, June. Dept. of Anthropology, Univ. of Calif.

37. Mudie, John D., 1962, A digital differential proton magnetometer, Archaeometry, v. 5, pp. 135-138.

38. Packard, M. and R. Varian, 1954, Free nuclear induction in the earth's magnetic field. Phys. Rev. v. 93, p. 941.

39. Rainey, F., and E. K. Ralph, 1966, Archeology and its new technology, Science, v. 153, pp. 1481-1491.

40. Ralph, E. K., 1964, Comparison of a proton and a rubidium magnetometer for archaeological prospecting, Archaeometry, v. 7, pp. 20-27.

41. Ralph, E. K., F. Morrison and D. P. O'Brien, 1968, Archaeological surveying utilizing a high-sensitivity difference magnetometer, Geoexploration, v. 6, pp. 109-122.

42. Royer, G., 1967, Two Years' survey with cesium vapour magnetometer, Geophysical prospecting, v. XV, p. 174.

43. Schwarz, G. T., 1967, A simplified chemical test for archaeological field work, Archaeometry, v. 10, pp. 57-61.

44. Scollar, Irwin, 1961, Magnetic prospecting, in the Rhineland, Archaeometry, v. 4, pp. 74-75.

45. Scollar, I., 1962, Electromagnetic prospecting methods in archaeology, Archaeometry, v. 5, pp. 146-153.

46. Scollar, I., 1963, A proton precession magnetometer with diurnal variation correction, Electronic Engineering, v. 35, p. 177ff.

47. Scollar, I., 1968, Automatic recording of magnetometer date in the field, Prospezioni Archeologiche, v. 3, pp. 105-110.

48. Scollar, I., 1968, A program package for the interpretation of magnetometer data, Prospezioni Archeologiche, v. 3, pp. 9-18.

49. Scollar, I., 1969, Some techniques for the evaluation of archaeological magnetometer surveys, World Archaeol. v. 1, pp. 77-89.

50. Scollar, I., and F. Kruckeberg, 1966, Computer treatment of magnetic measurements from archaeological sites, Archaeometry, v. 9, pp. 61-71.

51. Scollar, I., 1966, Recent developments in magnetic prospecting in the Rhineland, Prospezioni Archeologiche, v. 1, pp. 43-51.

52. Scollar, I., 1965, A contribution to magnetic prospecting in archaeology, Archaeo-Physika, Beiheft 15, Bonner Jahrbücher, Koln.

53. Slack, Howard A., Vance M. Lynch and Lee Langan, 1967, The geomagnetic gradiometer, Geophysics, v. XXXII, p. 877.

54. Tite, M. S., 1961, Alternative instruments for magnetic surveying: comparative tests at the iron age hill-fort at Rainsborough, Archaeometry, v. 4, pp. 85-90.

55. Waters, A. S., and P. D. Francis, 1958, A nuclear magnetometer, J. Sci. Instrum. v. 35, pp. 88-93.

III. NEUTRON ACTIVATION OF POTTERY (Abstract)

I. Perlman and F. Asaro
Department of Chemistry and Lawrence Radiation Laboratory
University of California, Berkeley

Significant progress has been made in neutron activation analysis of pottery as a result of a combination of factors: a powerful reactor; the novel lithium-drifted (silicon and germanium) detectors, which combine high resolving power with high sensitivity; high-quality computation facilities; and the accumulation of considerable experience and of a background of data. It is now possible to determine over 40 different elements in the pottery samples, although such a complete analysis is usually not made. Many of these elements can be determined to 1 percent, even if present only in concentrations of one part per million. In other elements, precision is only a few percent, and some can be estimated with even less precision. Because of the nature of the activation process, neutron activation analysis actually tends to be most sensitive for the elements normally present in low concentration.

The fundamental composition of the clays is very similar, but the minor and trace elements provide a characteristic fingerprint; thus, if enough elements are determined, it should be possible to characterize clays of a particular area uniquely.

The analysis of pottery is valuable because clay is one of the most ancient materials and is universally associated with man. People settling in a new area seem to have brought their pottery with them, but they soon started to use the clay that was available locally, while continuing to make ceramic ware in the style of their country of provenience. Therefore, analysis together with comparison of style provides good evidence of migration and transplanting of groups of people.

Neutron activation analysis yields a wealth of data, which, by their very quantity, present difficulties and bring out intrinsic complexities. The first steps in handling this information are to collect local pottery from one spot, establish a standard for the local production, and group the data. The dispersion of the individual groups is then established by statistical analysis. Any particular sample can be fitted into a particular group with a probability dependent on the dispersion of this group. An interesting example of the acuity of the procedure was found in the analysis of the clay plugs used for sealing certain predynastic Egyptian jars. The clay plugs were found to agree very well in their composition with that of "Nile mud" pottery found in the vicinity, and the body of the jars was quite similar to clay that was also found locally but which represented a material apparently used for different purposes.

An important question is how many (and which) elements are sufficient to characterize a shard adequately. Sometimes, but not usually, one or two elements are sufficient. The clay found in a place in southern Israel, for instance, is characterized by a high hafnium content (12 parts per million), whereas most other clays contain only 2 to 3 parts per million. In an analysis of a group of Cypriot pottery, one piece was found to contain this high concentration of hafnium, and the rest of the composition was subsequently found to match the clay from Israel.

Thus far, 1,400 pieces of Cypriot pottery have been analyzed to obtain a background on this type of ceramic ware. To provide a reliable analysis for an unknown Cypriot sample, an estimated 10,000 pieces will be needed. Similarly, an adequate study of the Mediterranean pottery would require about 100,000 pieces. The present rate of analysis is about 2,000 pieces per year. The rate of analysis may be increased, but the difficulty of handling and, particularly, of recalling the information needed for interpretation of results increases with the rate of acquisition of data.

To achieve high accuracy, it is necessary to irradiate a calibrated sample, as well as the unknown, for comparison. About 2 years was required to develop a reliable, homogeneous sample of suitable quantity, one which had a representative composition and filled all requirements for such a standard. Analysis can be made on a very small sample, but usually a 100-mg sample is taken by use of a sapphire drill. Even this quantity is small enough so that it can usually be removed in an inconspicuous place, thus causing no visible damage to valuable pieces.

IV. AUTHENTICITY TESTING OF CERAMICS USING THE THERMOLUMINESCENCE METHOD

S. J. Fleming
Research Laboratory for Archaeology, Oxford, England

Introduction

Thermoluminescence (TL) is the light emitted by a mineral when heated to 500°C in addition to the inherent red-hot glow which is associated with such high temperature treatment. The TL emission represents a release of stored energy from the mineral. The accumulation of this stored energy occurs over the archaeological burial time in the case of the minerals responsible for the TL observed when pottery fabric is heated.

The source of the energy storage is the trapping of electrons in the mineral's crystal lattice at defect sites and impurity ions, following the excitation of these electrons from lattice atoms by radiation from the surroundings of the pottery. This radiation environment consists of the trace levels of impurities of uranium, thorium and radioactive potassium (K^{40}) that are present in the pottery itself and the surrounding burial soil. Some radiation dosage also arises from the cosmic rays which continuously bombard this planet, but the contribution this involves is only approximately 3% (on average) of the total dosage experienced by the pottery minerals.

If the mineral is heated, the trapped electrons are forcibly released to wander once more through the crystal lattice until encountering their host lattice source atom (or an identical one elsewhere in the crystal) where they de-excite in recombination with their parent with the emission of that light which we term thermoluminescence.

Age Determination

The practical observation of this TL is illustrated in the schematic diagram of Fig. 1. During the heating of the sample on a nichrome metal strip the light emitted is detected by a photomultiplier which converts the light signal to an electrical current that feeds the y-axis of a chart recorder. Meanwhile a thermocouple records the temperature of the heating strip and plots the increasing temperature during measurement on the x-axis of the recorder. The curve obtained of TL versus temperature is termed a Glow curve (Fig. 2).

Common crystalline minerals will be mixed in the clay used for making pottery. During firing of the pottery (to as high as 1000°C) the TL accrued from geological dosage will have been driven off. If a sample of such pottery had been given an immediate reheat it would exhibit no TL.

In ancient times the pottery will have fallen into disuse and eventually have become buried. The thermoluminescence measured in present times represents a record of the radiation dosage of the burial conditions. It is assumed that this radiation environment of burial does not change during the archaeological life of the pottery i.e. the annual dose-rate is constant. The age of the pottery follows from:

$$\text{Age (years)} = \frac{\text{Total radiation dosage during burial}}{\text{Annual dose rate}}$$

Dose-rate evaluation

Firstly let us discuss some of the factors which control the evaluation of the denominator of this equation, and so limit the accuracy of the dating method. Precise dating has only become possible after close study of the various forms of radiation the pottery minerals experience. The alpha radiation which arises from uranium and thorium travels only 23 microns, on average, through pottery fabric. The beta radiation from these radio isotopes and from radioactive potassium travel approximately 1 mm, on average, in such fabric. These two forms of radiation are the source of internal dosage in the pottery. The surrounding soil supplies an external dosage component through the gamma radiation coming from the natural radioisotopes, effective from as much as 30 cms away from the buried ceramic. As mentioned earlier, cosmic rays also contribute some external dosage.

In quantitative terms average values for the different dosage components have been estimated from radioactive analysis of around 60 pottery fragments, and various soils from many different archaeological sites:

alpha radiation dose-rate	0.189 rads/year
beta radiation dose-rate	0.211 rads/year
gamma radiation dose-rate	0.067 rads/year
cosmic ray dose-rate	0.014 rads/year
Total dose-rate	0.481 rads/year

Short range alpha radiation contributes 39% of the total dosage on average. However, a further non-uniformity is present in pottery - the clay matrix contains almost all the internal radioactivity of the pottery while the crystalline minerals embedded in that matrix (such as quartz), are primarily responsible for the TL observed, but almost radioactivity-free (Fig. 3a). Grains of such quartz of radius larger than the alpha particles' range will have an internal region which has not been affected by this short-range radiation (see Fig. 3b). By gentle, controlled, crushing it is possible to extract the very small grains of quartz of dimensions around 1-5 microns which are fully affected by the alpha particles emitted by the clay matrix. Such control permits precise knowledge of the radiation geometry of the material used for dating to be retained.

Further, as the external dosage is around 17% the present estimated accuracy of dating of better than ±8% standard deviation for each pottery piece studied from archaeological contexts has only been possible by accurate radioactive analysis of the burial soil as well as of the pottery fabric itself.

Authenticity testing of ceramics

Such high accuracy is neither possible nor necessary in the majority of applications of the TL method to authenticity studies. It is not necessary since we may only require to distinguish between a piece of Chinese T'ang ware between 1100 and 1350 years old (if authentic) and a modern reproduction of such ware which might have an age of up to 60 years corresponding to the initial period of popularity of such T'ang material in the western art markets around 1910.

Nor is such high accuracy possible in authenticity studies for the following reasons. Firstly examine the form of sample usually used for this work. A 25 mg. powder sample obtained by drilling is treated as the practical limit to the quantity of material which can reasonably be removed from a figure without detracting from the artistic value of the piece.

The drilling procedure is at once a contradiction of the approach used for precise dating using controlled crushing. Now the sample contains a whole spectrum of grain sizes of crystalline inclusions. The spectrum is expected to differ from that of the original pottery structure as the drilling damages and fragments larger crystals and enhances the concentration of finer grains in the powder collected. The 1-5 micron grains are extracted from the drilled powder (by suspension in acetone, utilizing gravity - viscosity discrimination of grain size) and a series of samples prepared for TL measurement by deposition of around 1 mg. of the powder onto individual aluminum discs. Some of these 1-5 micron grains may well have originally been part of the inner regions of a large quartz grain. As this region received no alpha radiation dosage in the original radiation geometry of the pottery it acts as a diluent to the archaeological dosage now evaluated by TL measurement of these disc-deposited fine grains.

The true internal dose-rate suffered by the grains used for measurement must then be evaluated as: $f\alpha + \beta$ where $f < 1$.

Empirically using the data from the drilling of a limited number of pottery pieces of known age an effective value of f has been deduced of around 0.85. By continued study of pottery of various degrees of hardness it is anticipated that further information will be accumulated on this point.

More obviously damaging to any attempt at precise dating of art ceramics is the incomplete knowledge of the true level of environmental dosage for the ceramic's TL, since the piece has invariably been cleaned free of adhering representative burial soil by the time it begins its museum shelf-life, or appears in an auction sale-room.

It is true that we have a useful average working value for the environmental dosage of around 0.081 rads/year. To determine the maximum possible age of the ceramic we must know the minimum possible level of the environmental dosage. This is the contribution of cosmic-rays alone, assuming burial of the ceramic in a non-radioactive medium. This amounts to 0.014 rads/year.

The minimum possible age of the ceramic is controlled by the maximum possible level of the environmental dosage. The present level used is 0.170 rads/year corresponding to the highest level of activity determined from soil samples studied at the Oxford Laboratory. The possibility that the pottery spent its archaeological lifetime in the close vicinity of a uranium mine is presumed exclusive.

Thus for a piece to be authentic it is essential that its minimum possible age determined by TL does not overlap the documented era of forgery of such ware.

Further it is essential that the maximum age of a piece must not overlap the purported archaeological period of manufacture if that piece is to be declared an imitation.

Clearly the greater the gap between the archaeological period and the period of forgery (or imitation) the more certain it becomes that a definitive decision about authenticity can be obtained by TL testing.

Plate 1 illustrates the application of TL dating to authenticity testing of two significant art ceramics: (a) a Han Weasel, purported to date between 206 B.C. and 220 A.D., and (b) an Amlash Zebu Bull purported to date circa 1000 B.C. (The Amlash culture originates from the mountains of N.W. Persia overlooking the Caspian Sea. The Zebu is the domestic bull of that area).

The approach to dating the Han Weasel is initially to study the TL glow curves in order to establish in what temperature region the electron trapping, which is responsible for the light observed, is stable against thermal decay at ambient burial temperatures. This is achieved by comparison of the ordinates of the natural TL glow curve with those of the TL curve induced by laboratory radiation, at various temperatures. In the case of the Han Weasel this ordinate ratio becomes constant at and beyond 350°C. Subsequent dating analysis is only carried out on the portions of the curves above this temperature.

By comparison with the additinal TL induced by 1000 rads of beta radiation at 375^{o}C it is deduced that the natural TL at that temperature was induced by 1100 rads. Radioactive analysis on this figure yielded that the internal dose-rate from its clay fabric was 0.559 rads/year. Using the average value of 0.081 rads/year for the external dose-rate it is thus estimated that the figure experienced a dose-rate of 0.64 rads/year in antiquity. A date of 1720 years for the manufacture of the Weasel follows from these calculations. When the factors which determine the maximum and minimum age of the piece are introduced, date limits of 1330 to 2270 years are set, a result consistent with the originally suggested period of the Weasel's manufacture.

The date obtained for the Amlash Zebu is not so satisfactory with respect to authenticity. The natural TL glow curve is scarcely distinguishable above the background red-hot glow around 500^{o}C. Yet 150 rads of laboratory applied beta radiation induce substantial TL light levels in that temperature region. From these curves a limit of 6 rads is set on the archaeological dosage this piece has suffered since the last time it was fired. Radioactive analysis of the pottery clay yield a maximum age of 14 years.

The Copenhagen Amphora

It would be a simple task to illustrate this type of analysis time after time for over 200 pieces, many of them with some interesting special feature of either scientific or artistic value. The intrusion of this physical method into authenticity problems in the art world is well served by the example of the Copenhagen 'Pontic' amphora (Plate 2a). This amphora together with some similar pieces appeared on the Swiss art market in the 1950's. Doubts about the group were first voiced by Professor Dohrn in 1966, when several errors in painting were noted in production of the various 'heroic' scenes depicted on the amphorae. Depicted in the upper register of the Copenhagen amphora we find a scene of the death of Hector in which it is possible to suggest confusion between left and right in the artist's efforts. The assailant in the left of the scene is satisfactory, with the breat cuirass depicted simply by two linked circles, the shield held in the left hand while the right hand hurls a spear. In contrast the soldier attacking Hector from behind has the shield apparently held in the right hand while the spear is thrust by the left hand. Oddly, however, the sword sheath is painted on the left side of the warrior creating appreciable problems should he wish to withdraw that sword still holding his shield to the right.

Such confusion of left and right together with several other peculiarities of amphora decoration led Dohrn to conclude that the piece was a product of a modern imitatorill-versed in the techniques of ancient Greek artists. In response Hampe and Simon, in 1967, responded that these painting errors could well have stemmed from a similar lack of knowledge on the part of the plagiarists working in Etruria where this amphora is believed to have been made. Further these authors noted that even masters of Greek style on the mainland itself were not above such confusion of position, stressing the example of Nikosthenes in the amphora depicting Dionysos and dancing maenads and satyrs (Plate 2b). Note the kantharos held in the left hand, yet painted as a right hand.

TL dating was attempted upon a cube of 4mm. dimensions removed from the rim of the piece. Glow curves shown in Fig. 4 were obtained which suggested an archaeological dosage of 1365 rads, leading to a date for the amphora of between 420 B.C. and 2000 B.C. The authenticity of the piece was duly supported despite the sound artistic criticisms directed at it.

It is hoped that this method will continue to yield valuable information which can be turned to advantage in the understanding of the cultural development of early civilizations.

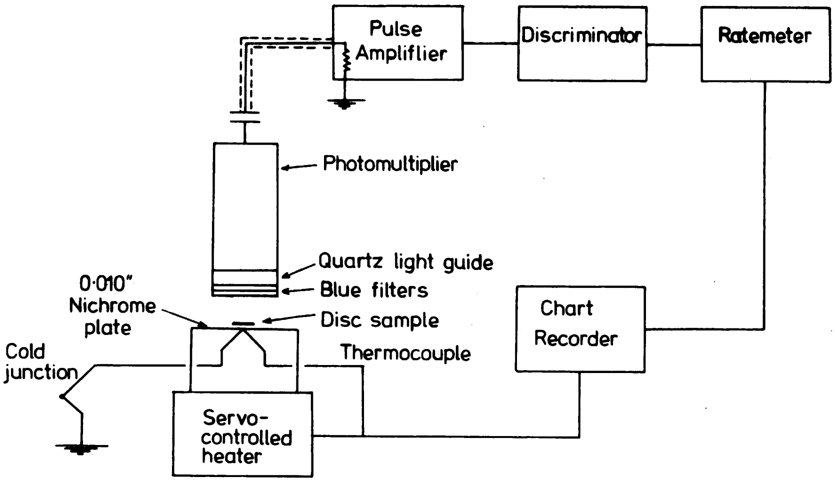


Fig. 1. Schematic diagram of the thermoluminescent apparatus (details of the electronics of the system are given in: Aitken, M. J., Alldred, J. C., Thompson, J. (1968) - Proceedings of the Second International Conference on Luminescence Dosimetry, Conf.-680920, 248. U.S.A.E.C. publication).

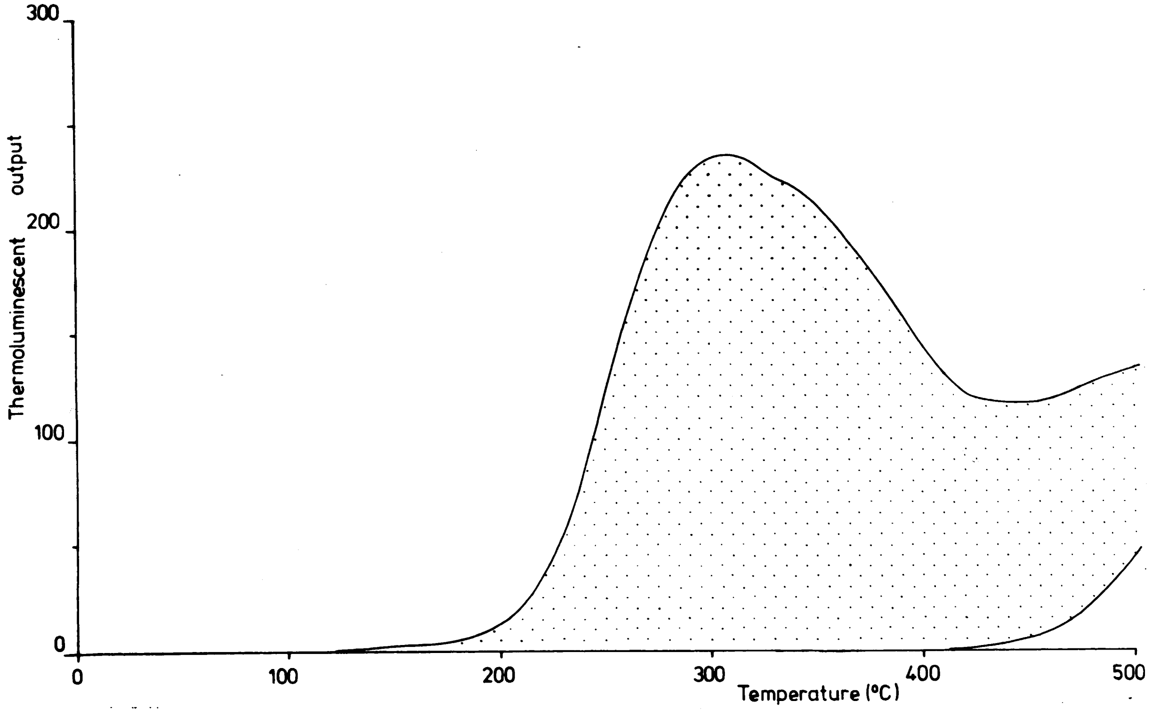


Fig. 2. A typical thermoluminescent glow curve from a sample of ancient pottery.

a

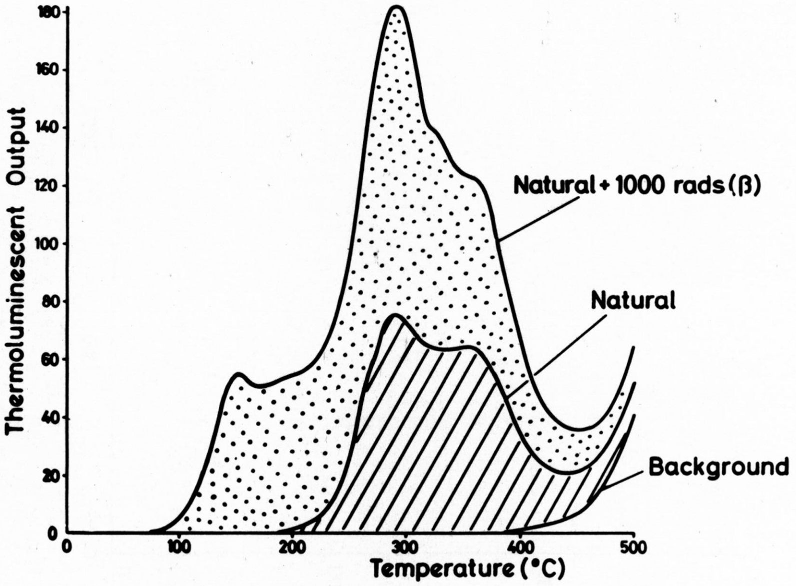


Plate 1a TL analysis of a Han Weasel

b

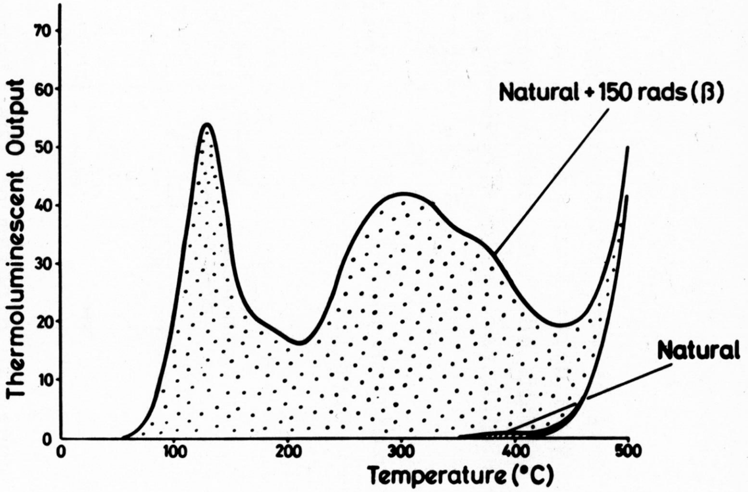
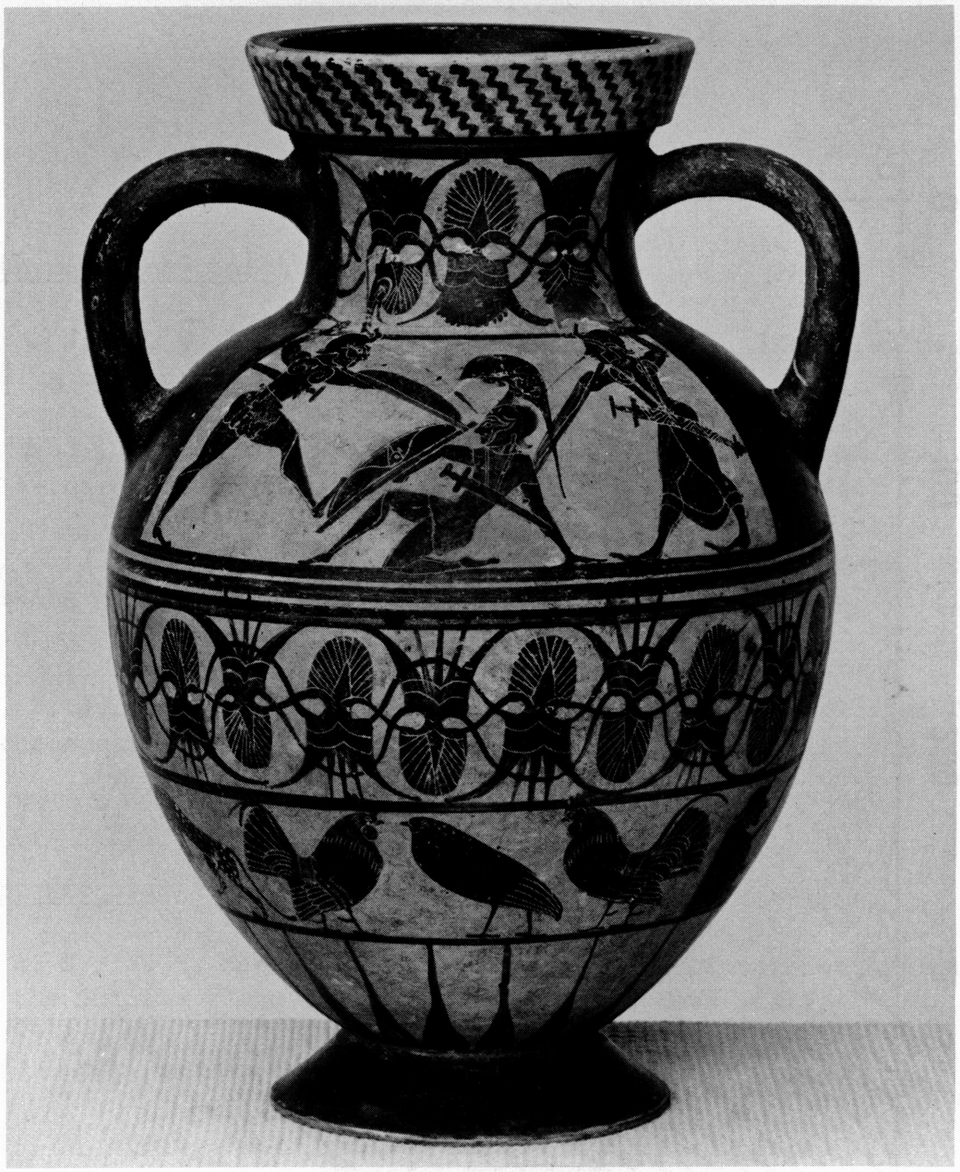


Plate 1b TL analysis of an Amlash Zebu



a

Plate 2a The Copenhagen Amphora

b

Plate 2b Amphora, by the Greek painter, Nikosthenes. Dionysos and dancing maenads and satyrs are depicted

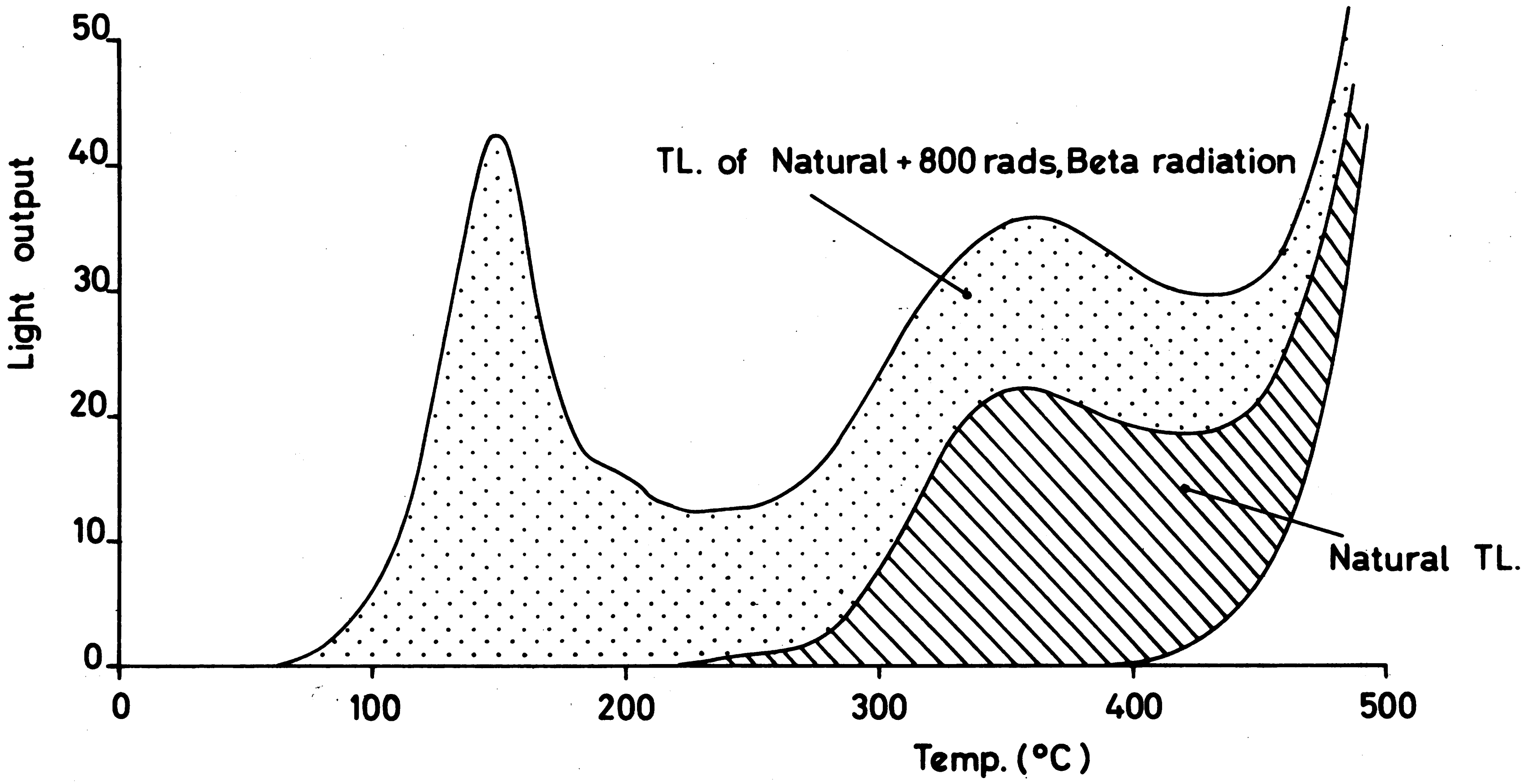


Fig. 4. TL glow curves for the Copenhagen Amphora.

References

a. Thermoluminescence

Aitken, M. J., D. W. Zimmerman, S. J. Fleming, 1968: 'Thermoluminescent Dating of Ancient Pottery'. Nature, vol. 219, No. 5153, pp. 442-445.

Aitken, M. J., 1969: 'Thermoluminescent Dosimetry of Environmental Radiation on Archaeological Sites'. Archaeometry, 11, pp. 109-114.

Fleming, S. J., H. W. Moss, A. Joseph, 1970: 'Thermoluminescent Authenticity testing on some "Six Dynasties" figures'. Archaeometry, 12 (1), pp. 59-70.

Fleming, S. J., 1970: 'Thermoluminescence dating by the Inclusion Technique'. Archaeometry, 12 (2), p. 135.

b. Art History

Joseph, A. M., H. M. Moss, S. J. Fleming, 1970: 'Chinese Pottery Burial Objects of the Sui and T'ang Dynasties'. (Hugh M. Moss Ltd.)

Dohrn, T., 1966: Bonner Jahrbuch, 166, p. 113.

Hampe, R., E. Simon, 1967: Jahrbuch des Römisch-Germanischen Zentralmuseums Mainz, 14, Jahrgang, p. 73.

V. PETROGRAPHIC CHARACTER OF CLASSIC MARBLES

Francis J. Turner
Department of Geology and Geophysics
University of California, Berkeley

Petrography.

Rocks are aggregates of mineral grains. Ideally each grain is a crystal or crystal fragment with a specific chemical composition - quartz SiO_2, calcite $CaCO_3$, potash feldspar $KAlSi_3O_8$ and so on. Standard petrographic procedure consists in microscopic examination of thin sections of rocks - about 1 cm in diameter, 0.02-0.03 mm thick, mounted on glass. Examination is carried out in polarized light, for this permits determination of optical properties related to crystal symmetry and peculiar to each mineral species. By this means two sets of petrographic characteristics of any rocks emerge; and both give valuable information as to the origin and history of the rock:

(1) The mineralogical identity of the component grains, the principal mineral constituents of most rocks being only half-a-dozen in number.

(2) Their mutual geometric relations which define the rock texture. The respective textural characteristics of volcanic rocks that have crystallized from melts, of sandstones laid down in water, and of metamorphic rocks that have recrystallized in the solid at high temperature and pressure, can be distinguished as such almost at a glance.

Nature of Marble.

Marbles are mineralogically simple rocks formed by metamorphic recrystallization of limestones (calcareous sediments, mostly originating as beds of shell and other organic debris laid down in clear marine waters). The main constituent is calcite, the common crystalline form of $CaCO_3$; and since statuary marbles are usually selected for purity and homogeneity the great majority contain more than 90 per cent, and some over 99 per cent of this single mineral. A principal component of a few marbles, among them some from the ancient quarries of Naxos, is dolomite, $CaMg(CO_3)_2$. During metamorphic recrystallization calcite crystals have grown to diameters of the order of 0.5 to 2 mm, and now build a closely interlocking mosaic. Metamorphic temperatures mostly lie within the range $250^{\circ}C$-$650^{\circ}C$. Under these conditions, maintained in rocks deeply buried for periods of 10,000 to 10,000,000 years, mineral impurities, notably clays and silica, when present, react with the carbonate matrix to produce new and characteristic metamorphic minerals readily identified with the polarizing microscope.

Non-Diagnostic characteristics.

From what I have said it is clear that all statuary marbles have much in common. Nothing of the unique character of marble from an individual outcrop or quarry is likely to emerge from routine chemical analysis, study by X-ray diffraction, or even from superficial microscopic examination by an "expert" lacking wide petrographic experience. Such techniques, valuable though they may be in identifying other materials, will merely tell us that we are dealing with rocks composed principally of calcium carbonate (calcite) with a minor-element pattern (trace of lead, copper, strontium, barium and so on) that is monotonously the same for most marbles. And this leads to a point of significance in evaluating "expert" opinion based on examination of archaeological materials by modern sophisticated techniques. However refined or complicated these may be, their use is justified only where they can yield new or more precise diagnostic information not obtainable by simpler and more commonplace means. A dozen years ago the Fogg Museum acquired a marble statue of Trajan. Critical as to its authenticity and history was the source of the marble from which it was carved. It was submitted to an "expert" who carried out detailed investigation by x-ray diffraction and spectrographic analysis and superficial petrographic examination. From all this there emerged, as could have been predicted by any mineralogist, the information that the Trajan statue is composed of uniform-grained marble with the chemical composition (including trace-element pattern) of almost any marble. Yet, on the basis of this evidence, the material was identified as "second grade Carrara marble;" and this pronouncement became an essential component of a lengthy reconstructed history of the statue, beginning in ancient Rome. It may well be that the story so put together is essentially true. The marble itself may well have come, as claimed, from Roman quarries at Carrara. But no compelling evidence to this effect has been presented; and the marble may equally well have come from any of a hundred sources, known or unknown, within or outside Europe.

Diagnostic Characteristics of Marble in Problems of Archaeology.

How then may petrography be of use in archaeological problems concerning classic marble? We commonly encounter two kinds of problems relating respectively to (1) the possible geographic source of a particular piece of stone, and (2) the possible matching of fragments supposedly broken from the same piece - especially in reconstruction of fragmented inscribed slabs.

Diagnostic petrographic characteristics that may contribute toward solution of such problems are those that reflect the imprint of the particular local episode of metamorphism by which a particular limestone was transformed into a particular marble. Metamorphism, it will be recalled, is a response to long-sustained high temperature and pressure over some period of geologic time. For Greek marbles this was probably during the Paleozoic era - perhaps 400-300 million years ago. The marbles of northern Italy - at Carrara, west of Florence, and at Lasa in the upper Adige Valley - were metamorphosed much later during the growth of the Alps, beginning perhaps 50 million years ago. The temperature-pressure conditions at any broad locality, e.g., in the

Pentelicon-Hymettus area west of Athens, or in the Carrara quarries of Italy, cover a limited range. Moreover, during metamorphism, which also involves intense deformation and flow of marble in the solid state - just as in the forging of red-hot metal - the pattern and degree of deformation are likely to differ from one locality to another; but at any one locality they are likely to be rather uniform.

The useful characteristics that we seek in marble for present purposes fall into three categories relating to texture, fabric and mineralogy:

Texture. The most obvious textural characteristic of a thin section of marble is grain-size. This tends to be highly variable from point to point on a quarry face, or even within a small slab or sometimes in a single thin section. The diagnostic value of the size criterion is correspondingly slight. Three characteristics that reflect deformational history, and so are more uniform in a given outcrop are degree of twinning, grain shape and configuration of grain boundaries.

Twinning. Any crystal subjected to stress at high temperature and confining pressure may respond by internal flow in a pattern dictated by the regular geometric arrangement of its component atoms. Seen in the simplest way the response can be envisaged as mutual displacement of adjacent planar arrays of atoms by analogy with sliding of cards in a card deck. By this means the grain elongates in one direction and becomes flattened in the direction perpendicular thereto. In special cases this process of slip or glide leads to development of thin laminae within which the atoms have become rearranged in a configuration symmetrically related to that in the host crystal. Such a reconstituted layer is termed a twin. Seen beneath the polarizing microscope twins are visible because their optical behavior differs from that of the host (Plate 1). Calcite is a mineral that twins readily under stress - especially at temperatures of less than about 500°C. The degree of twinning shown by calcite in marble tends locally to be rather consistent; it may differ significantly from one locality to another, or even from point to point in one quarry. Contrast the heavily twinned conditions of some grains in a marble from the Greek island of Kos (Plate 2a) with the paucity of twinning in a specimen from Paros (Plate 2c). On the whole twinning is not profusely developed in true classic Pentelic marbles -those from ancient quarry sites on the lower levels of Mt. Pentelicon (Hertz and Pritchett, 1953, p. 75, 77) - or in Hymettan marble from the Hymettan quarries (Plate 3a). It is even less conspicuous in most pure white Carrara marbles (Plate 4).

Shape and outline of grains. In marbles that were strained at rather high temperature without subsequent recrystallization, individual grains show a tendency for local parallel elongation (Plate 1a). Where recrystallization has outlasted deformation - or commoner situation - the grains show no such elongate shape and are said to be equant (Plate 2). Grain outlines may be highly irregular and interlocking (Plates 2, 3). More rarely when high-temperature recrystallization followed relatively cold deformation and was long sustained under stress-free conditions, the resulting grain boundaries tend to be planar. In the ideal case where surface tension at boundaries has been minimized the section shows points at which three boundaries intersect at about 60° (Plate 4a, b). Textures of this kind are characteristic of annealed metals. Combined properties of grain shape and outline are likely to be consistent within the limits of a single slab, or even within a quarry. Much of the high-quality marble from the Carrara quarries has equant grains with planar outlines - what we might call an annealing texture. Most specimens of Greek marble that I have examined - Pentelic, Hymettan or from Paros - have equant grains, often variable in size, with sutured or irregular boundaries. The few specimens that I have seen from Naxos are generally coarse, locally variable in size, equant and with some planar boundaries. Some Naxos marbles consist largely of coarse dolomite with sutured margins.

Fabric. A much more subtle set of structural characteristics, difficult to measure but consistent within a slab or even a large quarry, are what students of deformed rocks collectively term fabric. During rock flow under stress the individual microscopic crystals tend to become aligned in some symmetrical pattern related to that of flow itself. By analogy we may recall the respective patterns of logs in a flowing stream or of clouds in the steady trade-wind sky. It is not only by external shape that elongate grains become aligned. Even in marble whose grains are equant there is a pervasive though invisible pattern of orientation of the principal symmetry axis of the individual calcite grain. To bring out the pattern we must use specialized and rather laborious techniques of microscopy or X-ray analysis (cf. Weiss, 1954; Herz, 1955). But this is by far the most effective tool in problems relating to matching of fragments of statuary or of inscribed surfaces. If fragments match not only in direction and sense of inscription but also in the pattern and orientation of crystal fabric, the chances that they belong to the same slab are very strong indeed. Conversely, failure to match can be demonstrated with certainty.

Mineralogy. Much of the marble from the classic Dionysus quarry on Mt. Pentelicon is streaked sparsely with greyish green aggregates of the common metamorphic minerals chlorite, albite and epidote (Plate 3b) - all recognizable at a glance in a thin section. Occurrence of the same suite of minerals in marble of a temple such as that of Sunion is consistent with a Pentelic source, but is by no means conclusive proof of this; for impurities of the same kind are known in other mables. Some sources can, however, be excluded with certainty. Such is the group of quarries near Apollonia on the northeast coast of Naxos. All Naxos marbles that I have seen are almost pure calcite or dolomite. But if silicate impurities occur within them, it is impossible that they should include chlorite-albite-epidote. General experience of metamorphic petrography shows that this mineral assemblage can form at temperatures no higher than 350°. On the other hand sufficient is known of the geology of Naxos to indicate that in the general vicinity of Apollonia metamorphism was effected at temperatures of the order of 500°-600°C (Schuiling and Oosterom, 1967). Chlorite, albite and epidote could not coexist in this environment.

I have seen very little of Egyptian statuary marbles. Several specimens that I have examined microscopically contain silicates such as forsterite, Mg_2SiO_4, indicating conditions of metamorphism (local high temperature and low pressure) completely inconsistent with classic Greek and many north Italian sources (among these Carrara). The sources are probably local. The Egyptian marbles could not have come from classic Greek quarries. But as far as mineralogical evidence alone is concerned, the source could be located (though I think the probability infinitely small) in the Mojave Desert or the Sierra Nevada of California!

Mineralogical evidence accruing from petrography, relating to our present problem, leads mainly to exclusion of particular alternative solutions. Rarely we encounter evidence of a more positive kind. Some marbles are streaked with red, due to iron-oxide impurity in the form of hematite. Among the specimens collected by Herz from a classic Pentelic quarry is a red variety that in my experience is mineralogically unique. It contains the easily recognized red-to-orange highly refractive calcium-manganese silicate piedmontite. I know of no other marble from Greece or elsewhere that contains this mineral. Yet, by way of due caution, it seems most likely that somewhere, and quite possibly in Greece, another such rock may exist. Any slab of piedmontite-bearing marble found in Greece has most likely, but not certainly, come from Herz' source on Mt. Pentelicon.

Conclusion

Petrographic investigation can contribute a good deal toward solution of problems relating to sources or to matching of marble objects of archaeological interest. Only a start has been made in exploring the petrographic nature and variety of marble at a few classic quarry sites. Much more must be done, preferably by geologists. Badly needed, too, is extensive expert petrographic work on the objects themselves. This must be done by archaeologists, for only they can set up the problems and sustain interest in their solution. Any young student of classic archaeology who might care to include in his university training a few adequate courses in crystallography, mineralogy and petrography could make an immense contribution in this field. This is not so difficult a task as, for example, to master a language such as Russian or even German.

Finally it must be realized that archaeological problems in which the source of marble objects is crucially significant are seldom open to unique solution, Petrographic evidence may rule out certain hypothetical solutions as impossible. Others may be found consistent with the petrographic data, but no more than that. Very rarely a particular alternative may find petrographic support demonstrating probability almost - but never quite - to the point of certainty. But certainty, however much it tinges much of the opinion found in the older literature of classic archaeology and in the reports of some museum "experts," is not the goal of the scientist's quest. The petrographer, viewing from the outside problems of the kind we have been discussing, as clearly set out in the critical essay of Herz and Pritchett (1953) on "Marble in Attic Epigraphy," finds a paradoxical situation: pervading much of the pertinent literature of classic archaeology, as well as the reports of some "experts," there seems to be some reluctance to apply the principles of logic formulated - while some of the ancient quarries were operating, and others as yet unopened - by Socrates and Aristotle.

Acknowledgment

Financial assistance from the National Science Foundation (Grant GA-10636) is gratefully acknowledged.

Bibliography

Herz, N.: Petrofabrics and classical archaeology, Am. Jour. Sci., v. 253, pp. 299-305, 1955.

Herz, N., and W. K. Pritchett: Marble in Attic epigraphy, Am. Jour. Archaeol., v. 57, pp. 71-83, 1953.

Schuiling, R. D., and M. G. Oosterom: The metamorphic complex on Naxos (Greece), Proc. Koninkl. Nederl. Akad. Wetensch. Amsterdam, Ser. B, v. 70, pp. 165-175, 1967.

Weiss, L. E.: Fabric analysis of some Greek marbles and its applications to archaeology, Am. Jour. Sci., v. 252, pp. 641-662, 1954.

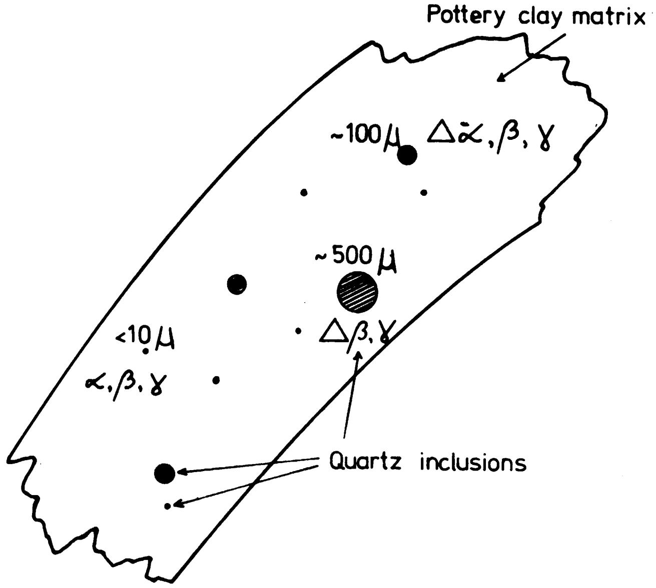


Fig. 3a. Radiation environment of crystalline grains embedded in the pottery clay matrix. For grains of ∼ 100 microns diameter the alpha radiation from the clay is attenuated by approximately 80%. For grains of∼microns the alpha radiation is almost entirely attenuated but now even the beta radiation from the clay is attenuated (by approximately 50%).

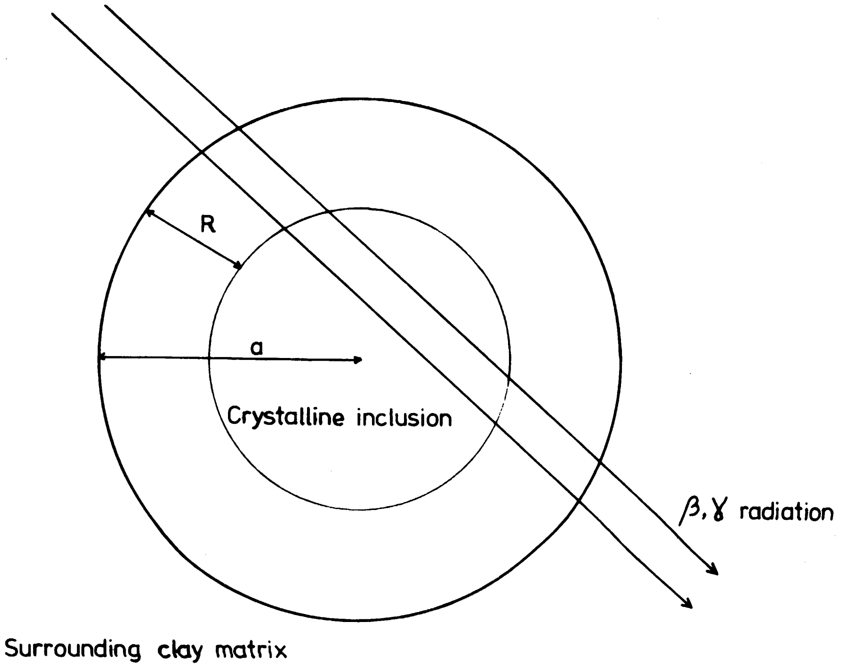


Fig. 3b. Alpha radiation attenuation by large crystalline grains. R is the maximum range of alpha particles in the crystal and a is the radius of the grain. As no alpha particles penetrate beyond a depth, R, into the grain, the inner regions experience only beta and gamma radiation during the burial of the pottery.

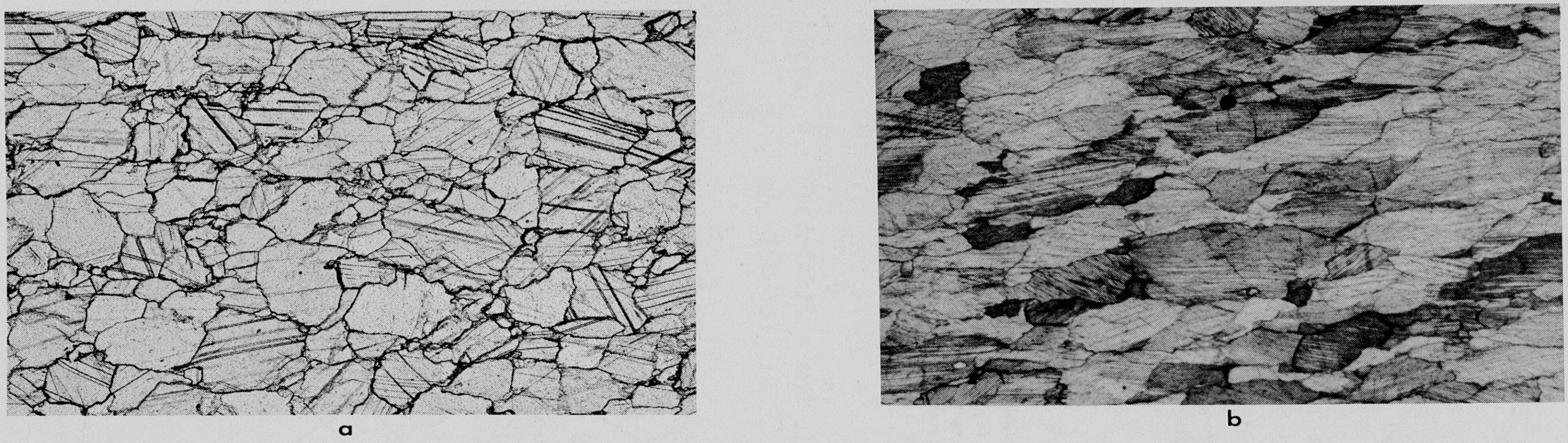


Plate 1. Thin sections of marble, Yule Creek, Colo. Transmitted polarized light. Lamellar structures are twins on $[02\bar{2}1]$ plane.

(a) Undeformed. X 10

(b) Experimentally deformed (shortened 19% by compression at 300°C, 5 kb confining pressure (D. T. Griggs). Note increased incidence of twinning, and grain elongation perpendicular to principal axis of compression. X 15

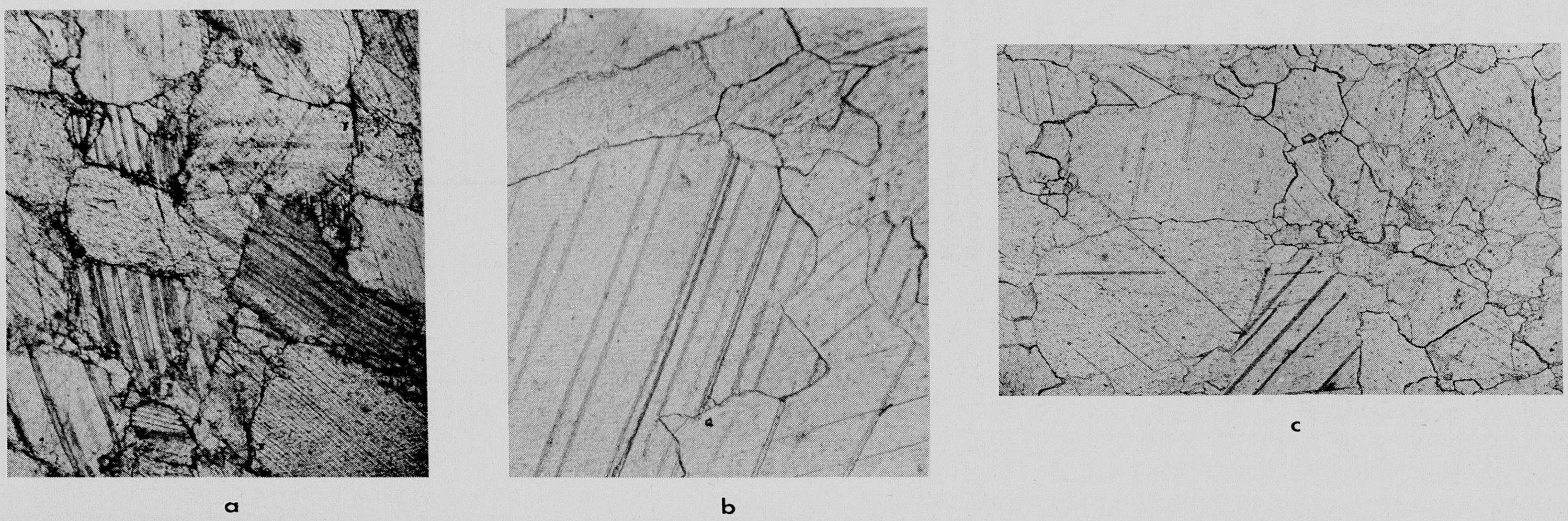


Plate 2. Thin sections of classic Greek marbles collected by N. Herz. Transmitted polarized light.
(a) Kos X 30 (b) Naxos X 85 (c) Paros X 30

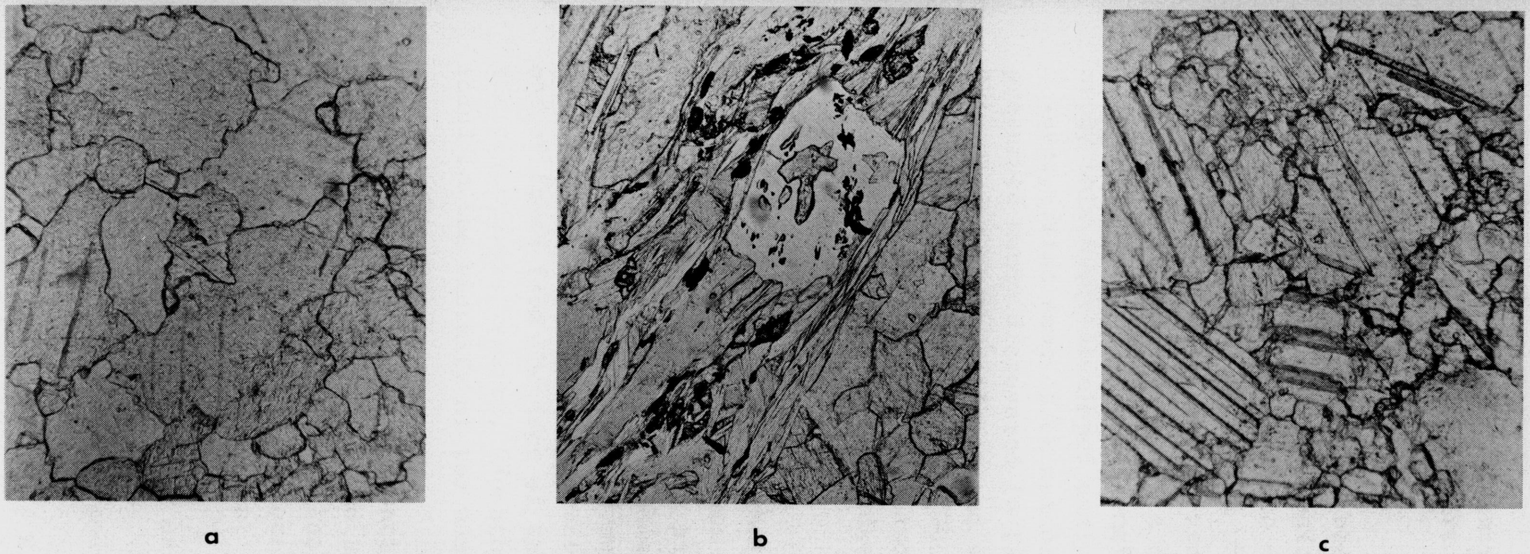


Plate 3. Thin sections of classic Greek marbles. Transmitted polarized light.

(a) Roman quarries Mt. Hymettus, Athens (N. Herz). X85

(b) Dionysus quarry Mt. Pentelicon (N. Herz); lower right half, calcite; upper left half, chlorite, albite epidote. X 30

(c) Temple of Sunion (said to be Pentellic). X 85

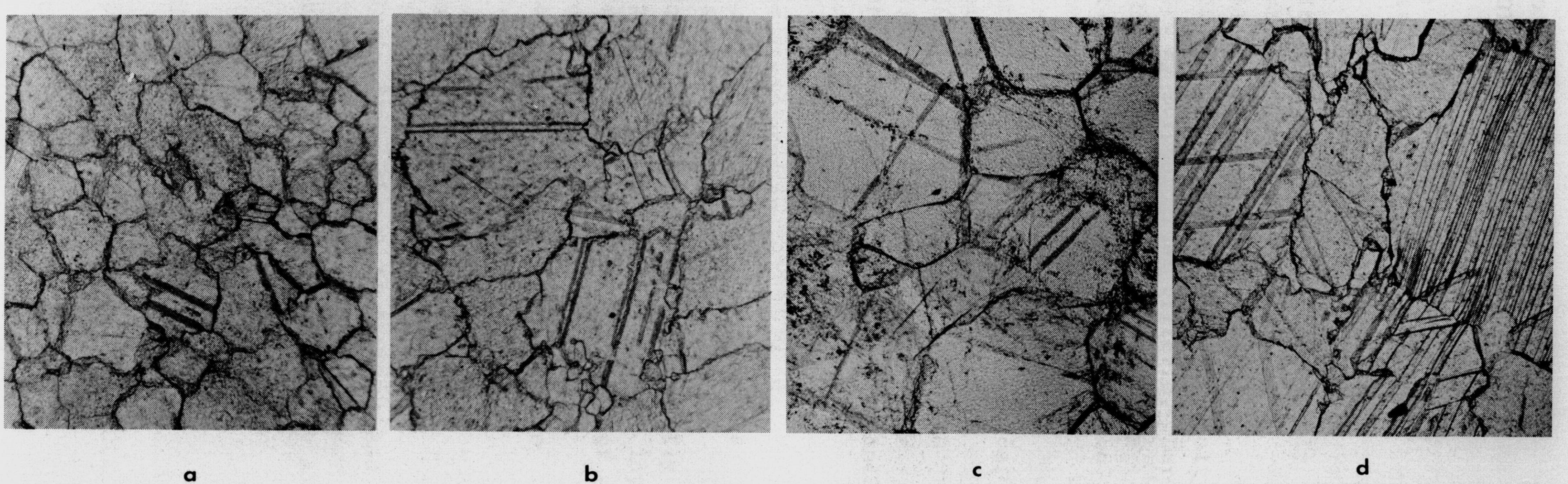


Plate 4. Thin sections of classic Italian marbles. Collected by author from modern quarries at old sites.

(a) Carrara X 85 (b) Carrara X 85 (c) Carrara X 30 (d) Lasa X 85

VI. NEW RADIOCARBON DATES BASED ON BONE COLLAGEN OF CALIFORNIA PALEOINDIANS

Rainer Berger[1], Reiner Protsch[2], Richard Reynolds[3],
Charles Rozaire[4], and James R. Sackett[5]

Until recently it has been difficult to date directly and accurately human bones found in archeological explorations. With the development of radiocarbon measurements based on bone collagen (Berger, Horney and Libby, 1964) a method was introduced which allowed a new assessment of the antiquity of Homo sapiens fossils that cannot be dated by morphological criteria. During the course of many years a number of human remains were found in California whose exact age had remained uncertain. It was therefore decided to apply this newly developed analytical technique in dating these specimens. However, first some check measurements were carried out involving a well-preserved mummy discovered in 1955 in Chimney Cave, Lake Winnemucca, Nevada. Skin tissue, bone collagen and vegetal clothing were dated by radiocarbon yielding dates of 2510 ± 80 (UCLA-690), 2500 ± 80 (UCLA-689) and 2590 ± 80 (UCLA-692) respectively (Orr and Berger, 1965). These analyses proved the equivalence of bone collagen dates with others derived from different organic materials.

The first California skull dated was discovered in 1933 by M. H. Wilson and E. H. Marriner, then teen-agers, at 255 St. Ann's Drive, Laguna Beach. It was removed with a pick-axe at a depth of approximately 1.75 m from the top of a steep embankment which road grading operations had shortly before cut along the entire front of this property. The skull apparently lay alongside the long bone fragments discussed below; it was the protrusion of one of these from the face of the embankment that had originally prompted the discoverers' search. No other faunal materials nor any artifacts were found in the vicinity of the human remains.

After a series of inconclusive consultations at both American and European museums the skull and some bone fragments were shown to L. S. B. Leakey who referred them for analysis to UCLA. Since the skull fragment had travelled to a number of different institutions it was first found necessary to establish if the specimen at hand was indeed the original. Fortunately a

---

[1] Departments of Anthropology and History, Inst. of Geophysics, UCLA.

[2] Department of Anthropology and Inst. of Geophysics, UCLA.

[3] Los Angeles County Museum of Natural History and Inst. of Geophysics, UCLA.

[4] Los Angeles County Museum of Natural History.

[5] Department of Anthropology, UCLA.

picture of the find had appeared in the Friday, January 15, 1937 issue of the Laguna Beach newspaper before it had left California. Comparison of the present skull with its marked scars with the original photograph appears to rule out substitution.

Portions of the skull, parietal and temporal bones, were dated as follows: 78.5 g of bones were extracted continuously with ether for several days to remove any organic substances introduced by handling the skull. Then the mineral matrix of the bones was destroyed by dilute cold hydrochloric acid treatment. Finally humic acids of different specific activity were extracted with dilute, cold sodium hydroxide. The remaining organic portion was dated and found to correspond to an age of 17,150 ± 1470 years (UCLA-1233A).

Later the long bone fragments associated with the skull were dated in an analogous manner. 23.0 g of bones yielded insufficient CO_2 for a finite date (UCLA-1233B). The age was calculated to be greater than 14,800 years confirming the late Pleistocene age of the skull bone fragments. The long bone fragments were identified as human by M. R. Urist of the UCLA Bone Research Laboratory. Casts of the fragments were made by the Department of Palaeontology of the Los Angeles County Museum of Natural History using a method avoiding organic carbon compounds.

The nitrogen content of the skull and long bone fragments was calculated based on the amino acid content. Furthermore, the fluorine content was determined by a colorimetric method and the uranium content by calculation from the radon present in the counting gas immediately after preparation or after a known elapsed time. Results obtained are listed below:

	N	F	U
Skull	0.26%	0.30%	60 ppm as U_3O_8
Long Bones	0.23%	0.34%	63 ppm as U_3O_8

Inspection of these data reveals that both types of bones are in all likelihood associated with each other.

One of the long bone fragments contained in its hollow small pieces of *Mytilus californianus* Conrad as determined by the conchologist of the UCLA Department of Geology, Mrs. L. Saul. This particular species of mussel shell differs from European varieties by a special rib structure. Since the long bones appear to be Californian and the chemical composition is similar to the parietal and temporal bone fragments a case can be made for the skull also being Californian.

The skull itself was analyzed by D. Stewart, Smithsonian Institution, whose preliminary analysis points out similarity of the Laguna skull with others found in the Santa Barbara region. Unfortunately the Laguna specimen is not complete which rules out an exhaustive analysis. Yet an examination of the character of the supraorbital ridges and the orbital portion suggests a female cranium.

The unexpected date of the Laguna skull prompted formal excavation aimed at securing additional _in situ_ material. During several weekends in the late Winter and Spring of 1968, a crew composed of 6 to 10 UCLA students working under the direction of J. R. Sackett conducted test excavations in all accessible areas of the St. Ann's Drive property. This included extensive excavation of the embankment which fronts the property, with particular attention being devoted to the area surrounding the original find spot as best this could be determined in consultation with W. H. Wilson. The work was subsequently continued periodically until January 1969 by digging crews working under the direction of Dr. Tomchak of Fullerton State College. A detailed report of all these excavations is now in preparation, but their largely negative results can briefly be summarized here.

The deposit is part of an alluvial fan that extends down one of the shallow estuary canyons which emanate from Hidden Valley Canyon above Laguna Beach. At least to the 5 m depth attained by excavation, the soil is composed of typical western coastal alkaline fine-grained sandy loam or outright yellow sand, in both of which turbulent lamellae may often be observed. Relatively homogeneous and free of concentrations of pebbles and rocks, the deposit exhibits little consistent bedding save for horizontal zones in which California mussel shells are concentrated. Assuming that the original find spot has been at least approximately located and that its soil was an integral part of the deposit seen today, the human remains would have occupied a stratigraphic position somewhere intermediate between two of these shell-bearing zones lying respectively 0.60 m and 2.0 m below the present surface of the embankment.

A shell sample from the upper zone has given an age of 8950 ± 80 years (UCLA-1349), while one from the lower has yielded a date of 8300 ± 80 years (UCLA-1364). For a skull some 17,000 years old to have been located between these very much younger shell layers would obviously entail a marked stratigraphic anomaly. This possibility cannot be ruled out given the geomorphological context of the deposit inasmuch as only erosion coupled with natural redeposition during mud flows or slides could have produced the inverted stratigraphy encountered with the insertion of much older bones between more recent depositions. But it must be stressed that the excavations have failed to yield any archeological or paleontological information that might be considered relevant to an explanation of the presence of the human skull and long bones. Indeed, throughout the excavations there was not obtained any substantial physical evidence to support the view that they were ever directly incorporated within the deposit. The likelihood is great that the origin of the Laguna Beach remains and their subsequent depositional history on St. Ann's Drive may never be known.

The second California skeleton which was analyzed is that of a woman found on 5 February, 1941 by L. E. Wyman during excavations in Pit 10 at Rancho La Brea (Merriam, 1914). Sometimes the escape of petroleum and natural gas over long periods of time can create enlarged chimneys in the soil along lines of least resistance with a diameter on the order of a meter. In fact, Pit 10 had two such chimneys topped by a common asphaltic cap which stood 1 m above the adjacent ground surface. At a depth of about 1.50 m the vents opened into a large dome-shaped asphaltic mass extending downward to unknown depth. One of the chimneys led to the surface directly while the other, which contained the human remains, extended 2 m horizontally and then abruptly sloped to the surface. Apparently the chimney containing human bones passed through an older asphalt deposit containing remnants of extinct late Pleistocene animals. Merriam recognized this circumstance and felt that the human bones were of Recent age.

Since the development of bone collagen dating, it became clear that a refinement was necessary to cope with the problem of petroleum-impregnated bones from the La Brea tar pits. Such a method was worked out in 1968 utilizing chromatographic separation of native amino acids in bones of extinct animals of the late Pleistocene (Ho, Marcus and Berger, 1969).

For preliminary analysis the left ulna had been submitted by C. Rozaire. However, for final analysis 55 g of bone representing the proximal two-thirds of the left femur were used. After grinding this bone to pass 60 mesh, the powder was pre-cleaned with acetone and treated in 1.0 N HCl at room temperature to dissolve the inorganic matrix. Subsequently alkali-soluble contaminants such as humic acids were removed by treatment with 0.1 N NaOH, also at room temperature. Then the sample was refluxed for 24 hours in 6.0 N HCl to complete hydrolysis of collagen into its component amino acids. The hydrolyzed sample was purified using an ion-exchange column charged with Dowex 50W - X8. After final elution with 5.0 N NH_yOH the amino acids obtained were dried, burnt and dated to be 9000 ± 80 years old (UCLA-1292BB).

From a morphological point of view the La Brea skeleton belongs to racial type not unlike the later Indians inhabiting Southern California (Kroeber, 1962). It belongs to a frail woman in her mid-twenties and consists of the following bones: skull, mandible, 4 vertebrae, a rib, left scapula, left pelvis and fragments of 6 limb bones. All the exterior surfaces of the bones have been polished by a process called "pit wear" which is thought to involve the abrasive effects of mineral grains suspended in moving asphalt (Stock, 1929).

What makes the La Brea skull interesting is a radiating pattern of fractures around a large irregular hole above the glabella suggestive of a depressed skull fracture. Today it is almost impossible to decide whether this damage caused death or is post mortem. Yet a complete mano capable of inflicting such a wound was recovered from a location 10 cm above the skull.

A third California skull fragment dated at UCLA is the so-called Los Angeles Man. It was discovered on 23 January 1936 during excavation work of WPA Project C-642 in a location north of the Baldwin Hills (Lopatin, 1940). Originally a skull consisting mainly of the occipital and two adjacent sections of the parietals, as well as several other human bones including a broken humerus were found in gray sandy clay some 4 m below the surface in the course of an ancient river bed. Despite excavation efforts to secure additional material only very small bone fragments but no tools were recovered.

On 13 March, 1936 workers found the remains of a mammoth at the same depth but 370 m distant from the human find. Unfortunately the whereabouts of the faunal material cannot be ascertained today. It was our plan to date these remains if possible in order to obtain a corroborating age determination. The fact that man and mammoth were found in late Pleistocene deposits suggested their very considerable age (Clements, 1938).

In the course of time only the skull has remained accessible as of this writing. It was brought to UCLA for dating by C. Rozaire. Since the skull is heavily encrusted with secondary carbonate cementation and appears to be more darkly mineralized, its age was presumed to be considerable. Therefore great care was exercised to obtain a reliable radiocarbon date from a portion of the skull bones.

For analysis ca. 100 g of bone were precleaned by scraping off extraneous material. Then the amino acids in collagen were recovered in a procedure similar to that used for the dating of the La Brea skeleton. Since the amount of bone used only yielded a partial filling of the UCLA proportional counter, no finite date could be calculated. This explains the final date of >23,600 years (UCLA-1430). Perhaps a finite date could have been obtained had most of the skull been used for amino acid isolation. However, this would have left little of the skull itself.

Since the facial portion of the skull is entirely missing, no definite inferences as to racial origin or sex can be made. However, the brain capacity has been estimated and does not differ from the average of that of other more recent Indians. As of now, this skull is the oldest directly dated human fossil in the Americas.

The most recent analysis of human remains from Tranquillity, California has shed more light on a complex archeological situation. A number of highly mineralized human skeletons were excavated under carefully controlled conditions by Hewes (1943, 1946) and by Satterthwaite (Angel, 1966). The site itself had been discovered in 1939 by the Hewes and Masseys in the Central San Joaquin Valley some 24 miles west of Fresno exposed as the result of erosion processes caused by changes in the drainage system between the Kings and San Joaquin rivers. At issue in the interpretation of the Tranquillity site was the question if man was indeed associated with an extinct late Pleistocene fauna as observed. However some of the cultural material found appears to belong to the California Middle Horizon of considerably more recent age. The enigma was further compounded by chemical analyses made by Heizer and Cook (1952) which suggested considerable antiquity for the human bones. Indeed, more recent microanalytical data for nitrogen and fluorine agree with this earlier investigation.

	N(%)	F(%)
UCLA analyses, this paper		
Human 6464A	0.04	0.11
6464B	0.06	0.12
Human 6073	0.03	0.12
Heizer and Cook, 1952		
Human 6073	0.060	0.208
6071	0.092	0.185
6072 A	0.110	0.156
B	0.072	0.102
6075	0.053	0.136

Tranquillity site consisted of a number of burials which yielded a considerable amount of human remains. For radiocarbon dating 1220 g of human bones from burials 3 and 4 were obtained through R. F. Heizer and A.B. Elsasser of the Department of Anthropology, University of California, Berkeley. First the bones were continously extracted with analytical grade solvents to remove any preservative or glue. Then they were treated in a similar manner as the Laguna skull. Finally the radiocarbon age was determined to be 2550 ± 60 years. As a result burials 3 and 4, as well as any bones with similar fluorine or nitrogen content, belong in context to the artifacts of the California Middle Horizon. At this point it is not entirely clear if all the human material found at Tranquillity is of the same general age. Moreover, we do not know the exact age of the faunal material either. However, on balance, a direct association between man and extinct fauna appears to be more a matter of geographical coincidence than a true tight association in space and time.

We wish to thank R. F. Heizer, L. S. B. Leakey, W. F. Libby, P. C. Orr and W. H. Wilson for support and encouragement in these studies. Furthermore, we are indebted to the Hancock Foundation of the University of Southern California, and the Isotope Foundation and National Science Foundation for grants.

Bibliography

Angel, J. L.
1966 Early skeletons from Tranquillity, California. Smithsonian Contributions to Anthropology 2 (1).

Berger, Rainer, A. G. Horney and W. F. Libby
1964 Radiocarbon Dating of Bone and Shell From Their Organic Components. Science 144:999-1001.

Clements, T.
1938 Age of the Los Angeles Man Deposits. Am. J. Sci.36: 137-141.

Heizer, Robert F. and S. F. Cook
1952 Fluorine and Other Chemical Tests of Some North American Human and Fossil Bones. J. Phys. Anthropol. 10:289-393.

Hewes, Gordon W.
1943 Camel, Horse and Bison Associated with Human Burials and Artifacts near Fresno, California. Science 97: 328-329.

1946 Early Man in California and the Tranquillity Site. Amer. Antiq. 11:209-215.

Ho, T.-Y., L. F. Marcus and Rainer Berger
1969 Radiocarbon Dating of Petroleum-impregnated Bone from Tar Pits at Rancho La Brea, California. Science 164: 1051-1052.

Kroeber, A. L.
1962 The Rancho La Brea Skull. Amer. Antiq. 27: 416-417.

Lopatin, I. A.
1940 Fossil Man in the Vicinity of Los Angeles, California. Proceed. Sixth Pacific Science Congress 4:177-181.

Merriam, J. C.
1914 Preliminary Report on the Discovery of Human Remains in an Asphalt Deposit at Rancho La Brea. Science 40: 198-203.

Orr, Phil C., and Rainer Berger
1965 Radiocarbon Age of a Nevada Mummy. Science 148: 1466-1467.

Stock, Chester
1929 Significance of Abraded and Weathered Mammalian Remains from Rancho La Brea. Bull. South. Calif. Acad. Sci. 28: 1-5.

VII. PRELIMINARY POTASSIUM-ARGON DATING OF EARLY MAN IN JAVA

Teuku Jacob and Garniss H. Curtiss

Professor of Anthropology
College of Medicine
University of Jogjakarta

Department of Geology and Geophysics
University of California, Berkeley

Specimens of volcanic rock collected in 1969 at the principal hominid sites in Java, namely Sangiran, Trinil, Ngandong, Ngawi, Modjokerto and Boetak, are now being dated at Berkeley. Owing to contaminants, mainly carbonate and zeolite, which contribute large quantities of air, it has been difficult to obtain meaningful dates from most samples worked on up to this time, but a fair date of 1.9 m.y. ± .4 for a tuff underlying the site of a mandibular fragment of Meganthropus can be reported. The Meganthropus fragment was found by Marks in 1952 in Djetis beds of continental origin near Modjokerto. Although the pumice tuff lies several meters below the hominid site, the site itself lies at least 400 meters below late Pleistocene beds all of which have been folded into an anticline and truncated by erosion, and it is believed that the pumice and hominid remains are penecontemporaneous.

The date of 1.9 m.y. makes this hominid, thought by many anthropologists to be an Australopithecine, contemporaneous with African hominids of similar evolutionary development. It seems reasonable to suspect that hominids were in southeast Asia long before Meganthropus was entombed at this spot in Java.

VIII. LITHO-MECHANICS AND ARCHAEOLOGY

Erich G. Thomsen and Harriette H. Thomsen
Department of Mechanical Engineering
University of California, Berkeley

Enduring stone gives us a glimpse of man's earliest constructive activity; it also presents us with unknowns. Can engineering and other physical sciences suggest some answers? Does the monumental stone of Chephren's Pyramid enclose passages and chambers? Alvarez (1), working with a team of U.S. and Egyptian investigators, has applied the special knowledge of nuclear physics, in an example of non-destructive exploration which may be applicable to New World structures. (Alvarez found that no major cavities existed in about one third of the bulk of the pyramid, but the remaining two thirds remain to be studied.) How was monolithic Malinalco carved from the living rock? An engineer has made a case for a method which fits the tangible evidence (2).

In proposing the application of engineering analysis to archaeological problems we wish to make a clear distinction between analysis, tested by experiment, and the very useful and valuable empirical work carried out by investigators such as Rau or McGuire(3). There is no intent to ignore or belittle the many years of experimentation and replicative attempts which on this continent, date back to the days of the Conquest(4).

Our concern with stone will be restricted to litho-mechanics, that is, to three topics each associated with manufacturing: fracture of glasseous materials in tool-making, use of stone fly wheels in drilling, and the manufacture of obsidian ear spools.

Fracture of Glasseous Stone.

Various suggestions have been advanced to explain the apparently consistent nature of fracture surfaces produced by man in the making of stone tools. Thus, for instance, it has been said that the prismatic cores often found in connection with blade-making and other worked obsidian pieces are due to planes of weakness in the material(3). Others have realized that flint, obsidian and other non-crystalline materials universally favored by man for stone tool-making have no preferred orientation. Consequently, the fracture surfaces must be rather the result of the special knowledge and skill of the tool-maker(5). A recent engineering analysis was made by Vaidyanathan(6) who considered that the two techniques most used by the early artisan, impact and pressure flaking, produce directions of fracture surfaces which fall entirely within predictable ranges.

It is a fact that brittle materials have a propensity to fracture when tensil stresses reach critical magnitudes. Tensile stresses are internal tractive or pulling forces per unit area which are largest on planes parallel to principal tensile-stress trajectories. Two examples, using chalk cylinders such as those employed for blackboard writing, will illustrate the nature of fracture along principal tensile-stress trajectories.

Writing chalk, largely calcium carbonate in a compressed form, responds to tensile stresses much like glass: (1) If a blow is struck of sufficient magnitude, squarely at the end of the chalk cylinder held in one's hand, a pressure wave will travel down the cylinder at the speed of sound, with a spherical front which is essentially at right angles to the axis of the cylinder. At the free end of the cylinder the pressure wave will become a reflective tensile wave. Fracture ensues across the cylinder if the tensile stresses are sufficiently high. This is the principle which was utilized by early man in splitting of flints; Leakey referred to this process as "quartering"(7).

(2) If the chalk cylinder is now twisted in one's fingers, the principal tensile-stress trajectories can be traced as helices on the surface of the cylinder which make angles of 45° with the axis. If the twist is of sufficient magnitude fracture is initiated and without fail, will follow this helical surface, thus illustrating that fracture in glasseous materials occurs in a predictable way.

The foregoing examples are used to illustrate the formation of facture surfaces in non-crystalline materials, when the stress system is simple. In actual stone tool-making this is seldom the case, but qualitatively the foregoing principles still apply. Because of the somewhat more predictable nature we will restrict our discussion to pressure flaking.

If a spherical indenter is placed on a flat glass or rock surface, referred to as a platform, then principal tensile-stress trajectories will be formed which will diverge from the pressure point as shown in Figure 1. The solution of this problem was first given by Hertz(8) and the stress distribution in the material under an indenter results in what are often referred to as "Hertzian stresses". Thus, an indenter placed squarely on the surface, with a thrust normal to the surface, gives the typical conchoidal fracture observed with prehistoric flint forms. If the indenter is now placed at an angle to the platform, then the fracture surface will follow trajectory 3-4 of Figure 2b instead of the trajectory 1-2 of Figure 2a. This solution was obtained by Hamilton and Goodman(9) for the case of a normal thrust combined with surface friction of an indenter, which is equivalent to placing the indenter at an angle.

While it is possible to obtain solutions for more complicated situations in pressure flaking, the foregoing examples illustrate the fact that stone tool-making can be analyzed by present day knowledge of fracture of brittle materials.

Perforated Stone Disks.

As an example of engineering analysis applied to an archaeological artifact we will cite the following:

Centrally-perforated stone disks (Plate 1a) are found in some profusion in central California archaeological sites; other specimens are cited from Nevada(10), and Woodbury (10) shows one from Arizona. The California stone disks are generally considered as a trait of the Late Horizon, where they are associated with the common marker trait of clam shell disk beads(11). Woodbury, apparently having only a single example, by association included it among Pueblo III-IV, and suggested that it might be a diffusion from Mexico.

We have not concerned ourselves particularly with the question of how these disks were manufactured; water-worn pebbles of similar size and contour are found in some of the central Californian streams. The improvement of such stones would have required a minimum of work, although the question of the achievement of the centering of the perforation might well raise some thought. There has been no general agreement on the purpose of these perforated disks. Some of them are very well-finished, many of them approach very nearly perfect symmetry in diameter and in the centering of the perforation; their narrow range of size approaching standardization makes it appear that they were purposefully made.

Kroeber(12) reported on the use by the Valley Nisenan (Southern Maidu) of a perforated stone disk as a "spindle whorl" in connection with the spinning of some fiber from a tule-like plant, but did not describe the disk in any detail. The weight of those measured by us (average weight 80-100 grams) would seem disproportionate to the fibers in general use in central California (e.g. Apocynum, Asclepias, nettle, iris); at any rate, such use as a spindle whorl does not seem to have been reported from California by any other than the single Nisenan informant. The association with the appearance of clam shell disk beads, as well as those of steatite and magnesite, suggested to us that the stone disks might have been used as fly wheels for a pump drill. A search of the literature disclosed that at least several other investigators had made similar suggestions(13). Similar disks of whalebone have been used as fly wheels for pump drills in New Zealand(13).

It should be pointed out that there is no archaeological evidence for the precontact use of the pump drill in central California(14). Barrett(15) advanced his belief that it had reached the Pomo via the first Spanish settlers. There is no account that the Coast Indians' contact with Drake in 1579 may have introduced them to such a drilling device, but it certainly cannot be ruled out. Hawthorne and Smith(16) include reproductions of two plates (IV and V), engraved by Stephanus in 1576, showing two pump drills as part of the equipment of a 16th century goldsmith's shop and their translation of Theophilus indicates that it may have been in general use in the eleventh century in Europe. The ethnological specimens of pump drills in the Lowie Museum collection all have wooden fly wheels and three-sided files modified for drill bits, hence must be of post-contact manufacture.

Lacking either archaeological or ethnological evidence for the use of these perforated stone objects we decided to subject the problem to engineering analysis. Were these stone disks of a size and weight which would have rendered them feasible as fly wheels in drilling?

Let us look at a variety of drill drives (Figure 3). The bow drill (Figure 3a) still used by the Eskimo, has not been reported from central California. The shaft drill (Figure 3b) appears to have been universally used, probably because of its simplicity. The thigh drill (Figure 3c) has been observed in use by the California Indians in the 19th century (17); so, too, has the pump drill (Figure 3d). McGuire (17) devised a string or thong drill which he called a "top drill"; we independently arrived at a similar device (Figure 3e). It is not known to have been used in California, nor have we any data on the use of the twist drill (Figure 3f). It should be noted that, except for the twist drill, all drill drives require reversal of motion in their action.

The question then arises: which one of these drill drives could have been used effectively for the production of small perforations, if a disk such as one of these had been attached as a fly wheel to a shaft? A drill shaft set in rotary motion by any means whatever will tend to stop as soon as the driving torque is removed. This is due to the fact that the angular momentum of the drill is small and not much energy can be stored. The torque applied overcomes friction and drilling work, but cannot impart enough energy to the drill shaft to keep it in motion. Thus a steady torque must be applied during each portion of the cyclic motion. If a fly wheel is attached to the shaft then torque can be converted to stored energy in the fly wheel by virtue of its rotary motion. The higher the rotary speed the greater is the energy storage in the drill. This energy storage can be utilized in overcoming friction as well as unwinding and rewinding the strings of the drill.

If we now examine these suggested drills we can at once eliminate those for which the fly wheel is of no benefit but will in fact be a hindrance. Thus drills (Figures 3a-c) which may be called constant torque devices can be kept in motion without a fly wheel. Even if they had been attached to the shaft as weights, the operator would find that he must expend extra energy when setting the drill in motion and again when the direction is reversed because of the angular momentum which it would then possess. Whenever the rotational motion is altered, energy must be expended by supplying additional torque which would give no benefit to the operator. Consequently, our analysis shows that only the string drill (Figure 3e), the pump drill (Figure 3d) and the twist drill (Figure 3f) could be used effectively with a fly wheel, assuming that a stone-age man would have the intelligence to discover for himself that technique by which he might reap benefits in expenditures of energy. We conclude, from our analysis, supported by our own experiments, that if the perforated stone disks were used as fly wheels, then any of the drills shown in Figures 3d-f might have been known in early California.

Aboriginal Manufacture of Obsidian Ear Spools.

We would like to discuss a further instance of engineering analysis as applied to the possible method of manufacture of an artifact widely regarded as one of the outstanding products of preconquest Mexico. We refer to the obsidian ear spools (sometimes called ear plugs), examples of which have found their way into most important collections of pre-Columbian art. Descriptions have dwelt on their beauty, their fragility, their paper-thin walls, but almost never on the significance of the technical know-how implicit in their manufacture(18).

Figure 4 shows types of ear spools examined in the course of our investigation of museum specimens of the United States and Mexico. This list is not necessarily complete but gives enough variety of types to permit some generalization of a characteristic, namely, rotational symmetry, and it is this aspect which has been subjected to analysis. This property was possessed to a high degree by nearly all of the surfaces of the ear spools examined. As a consequence of this high rotational or axial symmetry the walls of either cylindrical or conical sections of the ear spools were uniform, often only approximately one millimeter thick and the outer and inner surfaces were concentric within a range of 0.025 millimeters.

The realization of this high axial symmetry has posed the problem of what manufacturing method could the ancient artisan have used to achieve this remarkable feat? While it is possible to think of sophisticated methods for generation of such surfaces, we are proposing a simple one which could have produced the seemingly precise surfaces of revolution in so brittle and fragile a material and which was within the capabilities of the precolumbian lapidary. No attempt was made to replicate a finished ear spool; only sufficient experimentation was carried out to demonstrate the workability of the proposed method(19).

In describing the method, which we have called the "Two string floating center method," we will assume that an ear plug blank has already been prepared with a central perforation by a variety of possible operations with which the aboriginal stone-worker was familiar. We will therefore focus our attention on the generation of the external conical or cylindrical surface such that the inner bore and the new external surface will be concentric. We assume that the bored blank is mounted on a mandrel of bamboo or wood and fixed thereto with an adhesive such as a pitched string around the shaft at the two ends, as shown in Figure 5. The rotation of the shaft can then be achieved by wrapping two suspended strings once or twice each around the ends of the shaft and placing a weight at the bottom. Figure 6 illustrates the way in which the operator could clutch the spindle through a lap and set it in rotary motion by moving his hand up and down. The split lap held in the operator's hand surrounds the perforated obsidian blank and is provided with abrasive for the material removal action. The lap could be of wood or of a metal such as copper. The lap need not be close-fitting but must be replaced during the operation as the diameter decreases. A possible alternate position, utilizing a back-strap device is shown in Figure 6b. If the driving effectiveness is not good enough with that shown in Figure 6a, improvement could be achieved by placing larger driving cylinders over the two ends of the shaft. This reduces the rotational speed for a given up-and-down movement but increases the torque for overcoming lapping resistance. Furthermore, if the string has a tendency to slip during the upward motion of the operator's hand because of the reduced torque, which is due to a well-known principle of mechanics, then a teeter-totter arrangement could be provided as shown in Figures 6c and 6d. The single weight is replaced by two equal weights. This permits the weights to be lifted alternately so that one is suspended in air while the other is touching the ground, assuring equal driving torque in both directions for the lapping movement. The idea of two suspended strings appropriately weighted down could have come from the weaving techniques known to have been practiced early by aboriginal peoples.

The second important feature of the suggested technique is that the process tends toward the production of concentricity through Newton's second law of motion, one of the important principles in dynamics. In simple terms, it states that a mass in motion (rectilinear or rotary) will persist in motion until acted upon by gravity or inertia forces. Applying this principle to the manufacture of ear spools, assuming a balanced mass system, we see that the ear spool and shaft, if rotating at, say, constant speed, would be acted upon by gravity forces and the operator's push as he moves the assembly up and down. The material removal on the outer surface of the spool would be uniform and there is high probability that initial concentricity will persist. However, if the center perforation of the spool is <u>not</u> initially concentric with the outer surface in contact with the lap, then a small but sufficient centripetal or radial force will be produced because of the unbalance of the rotating mass. It is assumed that both the rotating spool and the stationary lap have sufficient masses to cause such a force, which will tend to abrade the eccentric portion of the surface more rapidly than it does the other. The important feature is that the correcting process is self-terminating, once concentricity will have been achieved.

The authors tested the hypothesis experimentally. In order to be certain that the material used was similar to those suggested by early chroniclers to have been the raw materials of the native lapidary, obsidian was collected from outcroppings at Zinapécuaro, State of Michoacán, México. Cylindrical ear plug blanks were arbitrarily selected for experiment. They were prepared by facing a rough block of obsidian and removing specimen blanks by core drilling. Diamond saws and core drills were used to facilitate the process. The outside and inside diameters were respectively 26.6 millimeters and 12.7 millimeters, and a length of 50.8 millimeters. These dimensions have no significance and were chosen because of the availability of core drills. The center perforation for each blank was drilled eccentrically in order to test the hypothesis of automatic center correction during the process. The abrasive used was Boron carbide of 280 grid size. Several lap materials were used in the course of the investigation (cast iron, copper, wood).

Plate 1b shows a cylinder of obsidian in which the outside surface was lapped and reduced from a diameter of 26.6 millimeters to 20.32 millimeters at a rate of approximately 0.025 millimeters per minute. The experimental results lead us to the following conclusions:

1. The proposed method works satisfactorily for the production of cylindrical ear spools.
2. A copper split-shell type lap gave satisfactory accuracy without requiring a close fit of the lap.
3. Dimensional accuracies in diameter over a length of 50.8 millimeters of ± 0.05 millimeters and a roundness of ± 0.025 millimeters could be maintained without special precaution.
4. An improvement of concentricity of 10% was achieved for a reduction of approximately 10% in diameter. The masses to accomplish this result need not be large (i.e., a lap of one-or two-pound weight at rotary speeds of approximately 10 rev./sec.) When large reductions in diameter are required, several laps should be used in order to improve or maintain concentricity.

In closing we feel it incumbent to raise the question: is information of this sort really useful to the archaeologist? Would McGuire's painstaking contribution to technology have been enhanced had he known that the silica group of stones is isotropic? Certainly precolumbian lapidaries produced consummate examples of art with no knowledge of "Hertzian stresses" or Newton's Laws of Motion. We feel that there is a practical application for lithomechanic studies such as these: sometimes their best function may be in the elimination of what are only seductive speculations. At any rate, the age of the Renaissance Man is past, and we are living in an era where the proliferation of data exceeds our ability to absorb it. The answer would seem to lie in an exchange of the special knowledge developed in all disciplines.

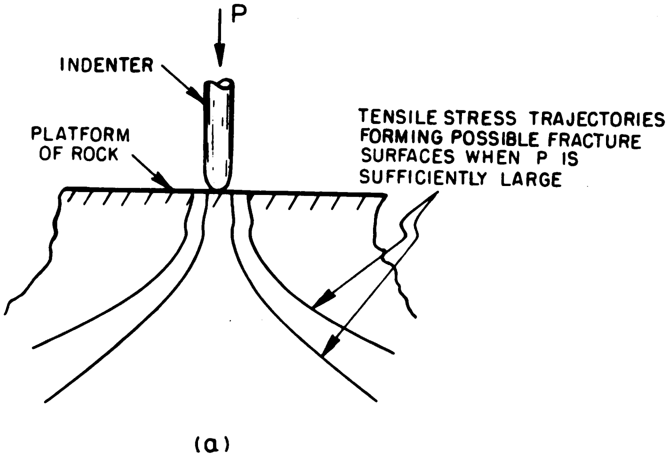
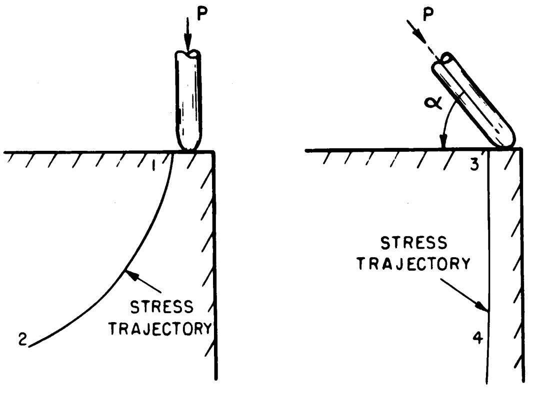


FIGURE I TENSILE-STRESS TRAJECTORIES INDUCED BY A BALL INDENTER UNDER LOAD P PRESSING ON A FLAT SURFACE



(a) NORMAL LOAD (b) LOAD AT ANGLE α

FIGURE 2 DEPENDENCE OF DIRECTION OF TENSILE-STRESS TRAJECTORIES ON DIRECTION OF LOAD

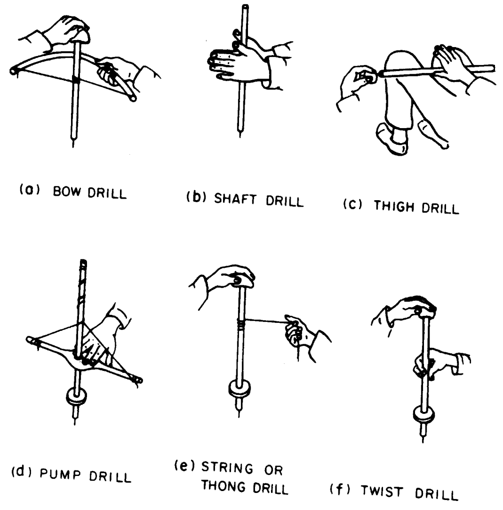


Fig. 3. Various Drill Drives

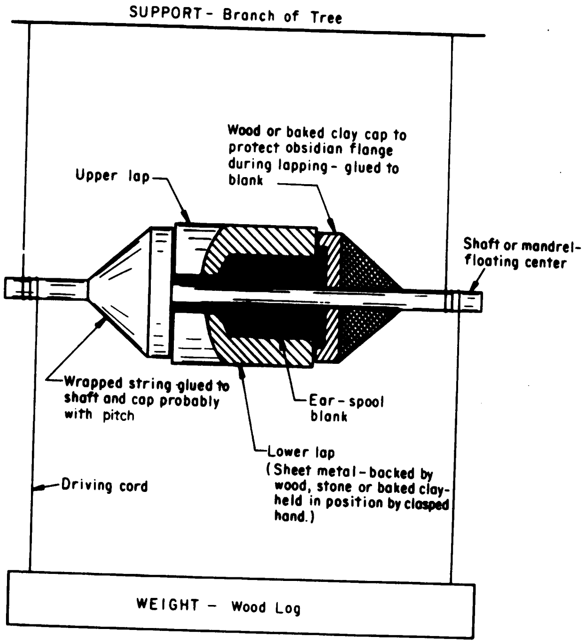
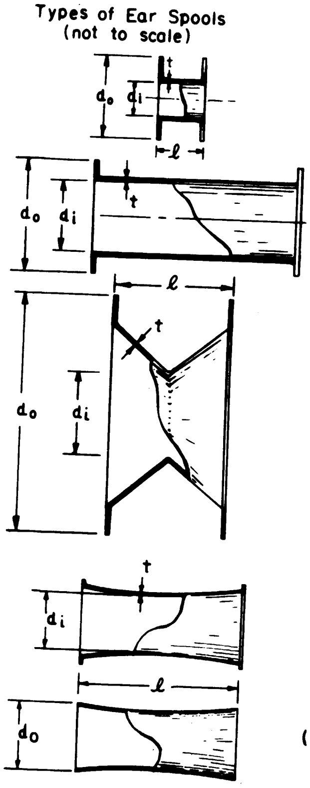


Fig. 5. Lapping Assembly



Typical Measurements mm

	d_o	d_i	ℓ	t
(1)	17.0	7.5	7.8	1.0
(2)	27.5	20.0	34.5	1.0
(3)	57	31	23	1.1
(4)	–	54	–	1.1
(5)	24	–	25	1.5

(Measurements of fragment)

Fig. 4. Types of Ear Spools

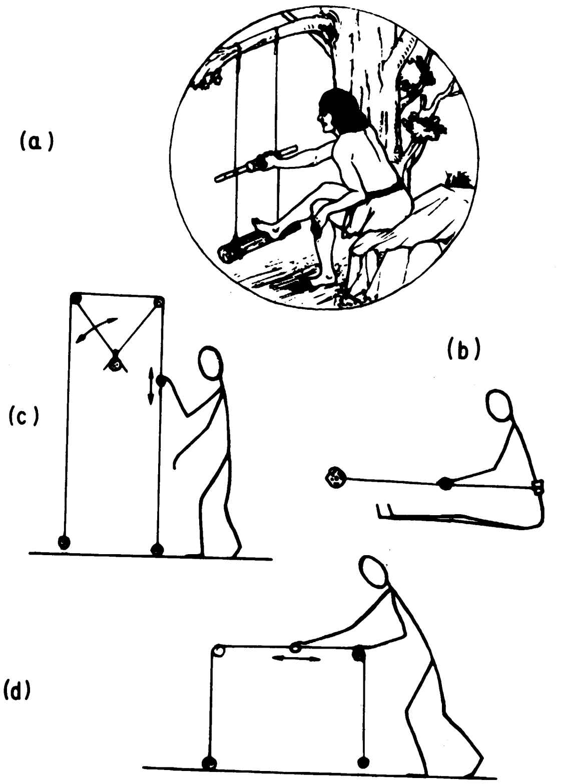


Fig. 6. Two-String Floating-Center Drives

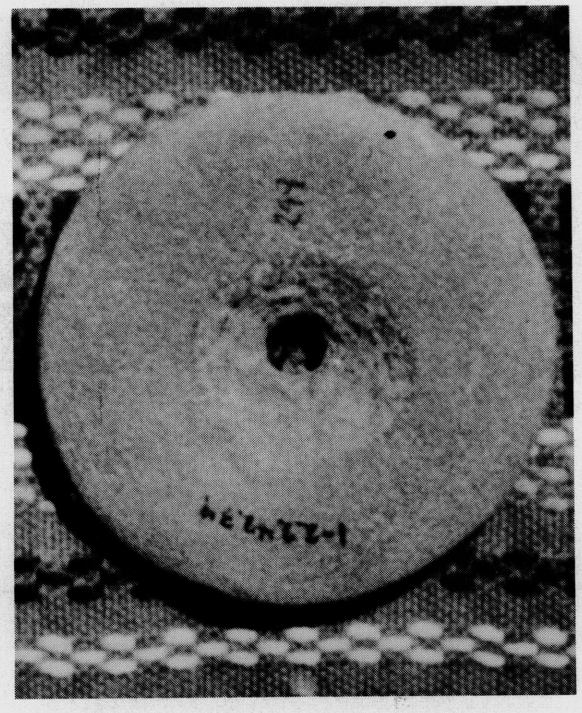


Plate 1a. Perforated Stone Disk (Specimen No. 1-224234, Lowie Museum, University of California, Berkeley.) Site: CCo-138. Dimensions: Diameter 7.5 cm, Diameter of pecked area, 3.5 cm, Diameter of perforation (biconical) .7 cm, Weight: 103.2 grams. Material: Fine-grained sandstone.

Plate 1b. Obsidian Blank and Lapped Specimen Produced by the Two-String Floating-Center Method

References and Notes

1. L. W. Alvarez, J. A. Anderson, F. El Bedwei, J. Burkhard, A. Fakhry, A. Girgis, A. Goneid, F. Hassan, D. Iverson, G. Lynch, Z. Miligy, A. H. Moussa, M. Sharkawi, L. Yazolino, Science 167,832 (1970).

2. J. O. Outwater, Jr., Amer. Antiquity 22,258(1957).

3. C. Rau, Smithsonian Inst. Ann. Rep. 1868,1(1869); Amer. Naturalist 15, 536(1881); J. D. McGuire, Amer. Anthropologist 5,165(1892); U.S. Nat'l Mus. Rep.(1896).

4. R. F. Heizer and J. A. Graham,(1970) (In press).

5. S. A. Semenov, Prehistoric Technology, M. W. Thompson, Trans.(Barnes and Noble, New York, 1964); D. E. Crabtree, Amer. Antiquity 33,446(1968); E. N. Wilmsen, Science 161,982(1968).

6. S. Vaidyanathan, Dissertation, Dep't Engineering, University of California, Berkeley(1970).

7. K. P. Oakley, Man the Tool-Maker, London,5th ed.,(1965); L. S. B. Leakey, Adam's Ancestors, Harper & Row, New York 4th ed.,(1960).

8. H. Hertz, Journ.f.d.reine u.angewandte Mathematik,91,156,Berlin(1881); Verhandl.d.Vereins Beförderung d.Gewerbefleisses,61,449,Berlin(1882); Gesammelte Werke,1,185,Fig.19,Barth,Leipzig(1895); Miscellaneous Papers,163,MacMillan,London(1896).

9. G. M. Hamilton and L. E. Goodman,Trans.A.S.M.E. Journ.App.Mech.33, Series E,371(1966).

10. M. R. Harrington,Indian Notes, Mus. of Amer. Indian,4,40(1927); L. L. Loud and M. R. Harrington, U.C.P.A.A.E.25,viii ff.,U.C.Press, Berkeley(1929); R. B. Woodbury, Rep.6,Awatovi Expedition,Peabody Papers, 34,185,Cambridge,Mass.,(1954).

11. H. C. Meredith,Prehistoric Implements,276
W. E. Schenck and E. J. Dawson,U.C.P.A.A.E. 25,385,U.C. Press, Berkeley (1929); R. F. Heizer and F. Fenenga,Amer.Anthropologist,N.S.41,378(1939); J. B. Lillard, R. F. Heizer and F. Fenenga,Bull.2,Sacramento Jun.Coll., (1939); R. K. Beardsley,Amer.Antiquity 14,1(1948); U.C.Arch.Survey Rep. 24,5-7(1954),U.C.Press, Berkeley.

12. A. L. Kroeber,U.C.P.A.A.E. 24,252, University of California Press, Berkeley(1929); Handbook of the Indians of California,Bull.78, Bur. Amer. Eth.Smithsonian Inst.Washington(1925)(Reprinted 1953).

13. Sir J. Evans, The Ancient Stone Implements, Weapons and Ornaments of Great Britain, 14, 2nd ed. London and Bombay (1897); J. D. McGuire, A Study of the Primitive Methods of Drilling, U.S. Nat'l Mus. Rep., 1893-4, 656, Fig. 46, Washington (1896); F. B. Chapman, Trans. and Proc. New Zealand Inst. 24, N.S., 479 ff. Wellington (1892).

14. W. H. Holmes, Handbook of Aboriginal American Antiquities, Part I, Bull. 60, B.A.E., Smithsonian Inst., 350 (1919); K. Birket-Smith, The Caribou Eskimos, Part II, 97, Copenhagen (1929).

15. S. A. Barrett, Material Aspects of Pomo Culture, Part II, Bull. of Pub. Mus. of Milwaukee, 20, 261, 308 (1952).

16. J. G. Hawthorne and C. S. Smith, On Divers Arts, The Treatise of Theophilus, Trans. from Med. Latin, University of Chicago Press (1963).

17. S. A. Barrett, Material Aspects of Pomo Culture, Part II, Bull. of Pub. Mus. of Milwaukee, 20, 285, Plates 47, 48 (1952); J. W. Hudson, Overland Monthly, 30, 101 ff., and Plate, San Francisco (1897); J. D. McGuire, U.S. Nat'l Mus. Rep. 1893-94, 718, Fig. 143, Washington (1896).

18. L. E. Mirambell, Tecnicas Lapidarias Prehispanicas, Investigaciones 14, Insto. Nac. de Antrop. e Hist., Mexico (1968).

19. E. G. Thomsen and Harriette H. Thomsen, Precolumbian Ear Spools: An Investigation of Possible Manufacturing Methods, (in press). (Contributions of the University of California Archaeological Research Facility, University of California Department of Anthropology, Berkeley, 1970).