

SENSITIVITY, PRECISION, AND ACCURACY: THEIR ROLES IN CERAMIC COMPOSITIONAL DATA BASES

Ronald L. Bishop, Veletta Canouts, Patricia L. Crown,
and Suzanne P. De Atley

Differences in analytical sensitivity, precision, and accuracy exist among techniques and laboratories involved in the chemical analysis of archaeological ceramics. Large differences in these analytical parameters become significant in the formulation of data bases where comparability of the data is being sought. Small differences become significant when comparing pottery produced from clay resources located within a discrete geological environment. To better assess and report on the analytical results being obtained from laboratories, neutron-activation analysis and X-ray fluorescence are discussed relative to the level of precision required for ceramic characterization studies, the use of standards, and the preparation and submission of samples for commercial laboratory analysis.

Las diferencias en sensibilidad analítica, precisión, y exactitud que existen entre distintos laboratorios y las técnicas que estos emplean en el análisis químico de muestras de cerámica arqueológica producen grandes diferencias en parámetros analíticos. Estas diferencias vienen a ser significativamente importantes en la formulación de bancos de datos para lo cual se busca compatibilidad en los datos. Así mismo, pequeñas diferencias vienen a ser significativas cuando se compara cerámica producida con fuentes de arcilla localizadas en una determinada area geológica. Para una mejor evaluación y reporte sobre los resultados analíticos obtenidos de los laboratorios, análisis de activación neutrónica y fluorescencia de rayos X son discutidos en relación con el nivel de precisión requerido para la caracterización de estudios cerámicos, el uso de standards, y preparación y presentación de muestras para análisis comercial en el laboratorio.

Ceramic compositional studies using various types of chemical analysis are becoming more frequent in the United States as archaeologists refine their questions about ceramic production and distribution (e.g., Bishop 1987; Bishop et al. 1988; Crown 1983; Crown and Bishop 1987; Deutchman 1980; Olinger 1987a, 1987b, 1988; Tuggle et al. 1982). These studies share in common the need to "characterize" some body of ceramic material through chemical analyses. Assuming that ceramics made from the same clay resources will be more similar chemically, and that sources of paste variation are understood, archaeologists have a powerful tool with which to differentiate local from nonlocal ceramic materials. These data then are used in developing models of ceramic production and distribution that, in turn, are related to more comprehensive models of social interaction and exchange networks.

Systematic chemical analysis of ceramic pastes had to await post World War II developments in instrumental technology (Earle and Ericson 1977; Harbottle 1982b). Even with new instrumentation, however, compositional analyses of archaeological ceramics generally remain expensive and time consuming. Recently, some investigators have taken advantage of the proliferation of commercial laboratories offering low-cost analyses. This new development significantly augments the availability of analytical resources, and as more archaeologists employ the services of these commercial laboratories, the number of chemically based analyses will amount to an accumulated data base of several thousand samples within a relatively short time. Archaeologists, up to this point, have tended to rely on the judgment of their analytical collaborators for the generation of "adequate" or "good" data. However, the increasing reliance on analytical data purchased from several commercial lab-

Ronald L. Bishop, Conservation Analytical Laboratory, Smithsonian Institution, Washington, DC 20560
Veletta Canouts, Archeological Assistance Division, National Park Service, Washington, DC 20013 and Conservation Analytical Laboratory, Smithsonian Institution, Washington, DC 20560
Patricia L. Crown, Department of Anthropology, Southern Methodist University, Dallas, TX 75275
Suzanne P. De Atley, Research Associate, Museum, University of Colorado, Boulder, CO 80309

American Antiquity, 55(3), 1990, pp. 537–546.
Copyright © 1990 by the Society for American Archaeology

oratories demands that the archaeological consumer develop a greater understanding of the type and quality of the data being obtained. For example, how do the different data sets relate one to another? To what extent can data produced for one area be compared to those produced for another? Can future researchers incorporate and build upon data already obtained? And, perhaps at a more fundamental level, can the data produced by a single project be considered internally consistent?

This presentation calls attention to the roles of analytical *accuracy*, *sensitivity*, and, especially, *precision* in assuring the quality and comparability of data held within a common ceramic compositional data base. We focus attention on the analytical techniques of X-ray fluorescence (XRF) and instrumental neutron activation analysis (INAA) because they have been the primary instrumental methods employed in the chemical analysis of archaeological ceramic materials. References to the application of these techniques and others in the study of archaeological ceramics are given in Bishop et al. (1982) and Harbottle (1982b).

Omitted from the discussion are the issues of research design and data synthesis (Bishop and Neff 1989). At issue here is the ability of archaeologists to obtain "good" analytical data that can answer the specific questions being posed and that can be pooled with other data that are stored in an analytical data base for later use.

ANALYTICAL CONCERNS

Analytical sensitivity, precision, and accuracy are major concerns of laboratories engaged in instrumental analyses. In order to convey this information to users and analysts in other laboratories, the results of data analysis are accompanied by information regarding the analytical parameters including, among others, the type and configuration of the instrument, sample size, and counting statistics. As Ives (1975) commented over ten years ago, these parameters often are not reported in publications, and thus, there is neither adequate information on which to judge the extent of error in the measurements, nor is there information that can be used to replicate and compare the analyses. Despite these concerns, we realize that the majority of the archaeological consumers of analytical data are not sufficiently aware of the importance of this information for monitoring the quality of data that they are acquiring.

The comparability of data either within a single project's data set or between different projects is of great concern to archaeologists. Indeed, the problems facing archaeologists who are contributing to a growing ceramic compositional data base are similar to those encountered in accumulating radiocarbon dates, for example. The methods and techniques of radiocarbon dating have undergone continuous evaluation, and users are quite sophisticated in their knowledge of biases and differences among laboratories. Concerns about the comparability of information among laboratories still abound even for this well-established analytical tool, however (e.g., Kra 1986; Wilcock et al. 1986).

Sensitivity, accuracy, and precision are everyday, working scientific constructs. Their roles have been discussed explicitly by researchers engaged in the chemical analysis of archaeological ceramics (Harbottle 1976; Perlman and Asaro 1969). While the earlier discussions remain sound, constantly evolving refinements in methods and techniques need to be summarized and assessed at regular intervals in order to mark the progression of the methods. Even though scientists conducting neutron activation analysis, for example, have compared results from different laboratories (Harbottle 1982a; Yellin et al. 1978), more comparisons that include the new commercial laboratories are now necessary. The commentary presented below is not exhaustive. Rather, we call attention to the analytical concerns that must be addressed by new individuals and new laboratories as they become involved in ceramic-compositional studies.

Sensitivity

An investigator will need to employ an analytical technique that is "sufficiently sensitive" to determine differences, often what may be minute differences, among products made from different raw material resources. As used here, sensitivity primarily refers to the minimal amount of an elemental concentration that can be detected given the experimental conditions. Sensitivity will vary according to technique. From a practical standpoint, for an individual project, the sensitivity

of an analytical technique need only be commensurate with the level of (archaeological) discrimination being sought within the data.

Consideration of sensitivity must be combined with concern for (1) the time involved in sample preparation, (2) the number of elemental determinations, and (3) the analytical throughput of samples. The available techniques that have been applied to archaeological ceramics investigations differ rather markedly in these variables.

XRF has been used extensively for qualitative or semiquantitative analyses because it can be quick and inexpensive, but there is a cost in reduced sensitivity relative to other potential laboratory techniques (Crown 1983; Crown et al. 1984; Culbert and Schwalbe 1987; Olinger 1987a, 1987b, 1988). Generally speaking, the elemental determinations obtained through nondestructive, qualitative and semiquantitative analyses for a ceramic sample by XRF reflect the clay mineralogy and the type of naturally occurring nonplastic materials or added temper mixed within the ceramic paste. That is, XRF utilized in this way probably would be sufficient to differentiate among similarly tempered ceramics if different kinds of clay mineral were represented in the sample. Alternatively, chemically expressed differences could be found among pottery made from clays that were similar mineralogically but which contained different kinds of temper. The extent to which XRF analyses can differentiate among pottery made from mineralogically similar clays *and* tempers is limited. Fully quantitative XRF analysis greatly increases the ability to compare data among laboratories but with a concomitant cost in the size of sample removed for analysis, sample preparation, and count time.

In comparison to a fully quantitative XRF analysis, INAA is more sensitive and can detect some elements having concentrations as low as a few parts per billion. This sensitivity has contributed to its recognition as the "technique of choice" by several analysts conducting ceramic investigations (e.g., Harbottle 1982b; Rapp 1985). One advantage of obtaining quantitative data on the paste constituents that occur in trace amounts lies in the fact that whether or not the elements are depleted or concentrated in different mineral phases depends upon local geochemical processes occurring during rock formation (Levinson 1974). Because INAA is sensitive to low elemental concentrations, it is, therefore, sensitive to the minute differences that can occur within a geochemical formation. Thus, the determination of several trace-elemental concentrations that differ in their chemical properties will tend to produce a highly specific fingerprint for a clay resource.

Sensitivity plays but one role in achieving analytical adequacy. This fundamental requirement only assures us that an analytical measurement can be made. How *good* that measurement is is best described by the accuracy and precision of the analysis.

Accuracy

Accuracy is a statement of how close a measurement of an element is to its actual concentration in a sample. By their nature, instrumental techniques such as XRF and INAA are relative techniques. They do not measure the abundance of a component directly but rather record some physical property of a component under certain conditions (Harbottle 1982a). A standard of known elemental concentration, subjected to these same conditions, generally is used to measure accuracy.

Most laboratories today use one or several well-analyzed reference materials against which the concentrations in unknown samples are calculated. Several of the better-known standards in ceramic research are AP Standard Pottery (Perlman and Asaro 1969, 1971), USGS Standard Rocks (Flanagan 1967, 1969, 1979), the Brookhaven "in-house" Ohio Red Clay (Yeh and Harbottle 1986), and the National Bureau of Standards SRM1633, Coal Fly Ash (Blackman 1986). Harbottle (1982b) notes that in the early 1970s each laboratory was working more or less in isolation. As large, overlapping data sets began to accumulate, the utility of exchanging data between laboratories became obvious. To make the data comparable, the laboratories needed to use the same standard material or, if using different standards, they needed to derive conversion factors that would allow one laboratory's data to be normalized to the standard of another (e.g., Olin and Blackman 1989:Table 1). The normalizations used today, while not without error (see Yeh and Harbottle 1986), seem to be well within the working limits for most ceramic-characterization requirements.

Precision

Analytical precision is a statement of how well we can repeat the analysis and obtain the same results. Assuming a representative sample, the nonreducible amount of error that will occur in an analytical determination is a statistical consequence of inherent randomness in the measurement process, that is, counting statistical errors.¹ Additional limitations on precision can result from inadequate sample preparation, especially the insufficient homogenization of the sample. The exact magnitude of all of the different errors is difficult to determine directly but all contribute to the total variation encountered in chemical analyses of archaeological ceramics—variations that affect our ability to make distinctions among analyzed groups of pottery in studies of ceramic production and distribution.

We stress the importance of analytical precision for two reasons: (1) it contributes significantly to the observed elemental variation; and (2) it is among the most controllable factors in an analysis. As discussed by Harbottle (1976), the total variation, S_T^2 , can be expressed by the formula

$$S_T^2 = S_N^2 + S_S^2 + S_A^2$$

where S_N^2 represents the natural variance of an element's concentration, S_S^2 is the sampling variance, and S_A^2 is the variance introduced in the analytical process such as weighing error, counting statistical error, peak integration, background subtraction, counting geometry, etc. S_A^2 also includes errors introduced by inhomogeneities in the "standard reference materials" relative to which final unknown concentrations are determined (see also Yellin et al. 1978). Repeated sampling and repeated analysis of a given material results in a spread of values about a determined elemental mean concentration which is used to indicate the *overall* analytical precision.

If, for the sake of the present discussion, we assume that the ceramic objects have been sampled in such a manner as to minimize error resulting from heterogeneity in the ceramic pastes (S_S^2), then the remaining variation is a function of the inherent natural variation and the analytical procedures ($S_T^2 = S_N^2 + S_A^2$). The magnitude of the total error will limit our ability to determine the parameters whereby ceramic products from a resource procurement site, region, or zone, can be differentiated from other similar spatial units.

Our primary concern here is with the extent to which the errors that are a consequence of the analysis will enlarge the variation to a point that is appreciably beyond the natural variation within a resource system. The greater the variation beyond that which occurs naturally, the greater will be the likelihood of blurring the compositional distinctions between otherwise separable resources.

The degree of analytical precision required for an investigation is dependent on the question(s) being posed by the investigator, but an attitude of "the more, the better" appears warranted. Generalizing from our observation of both inter- and intraregional studies of New World pottery, analytical determination of several elements, spread over different chemical series, with an analytical precision at or below 5 percent error appears to provide a useful working level. Analytical precision falling between 5 and 10 percent is a very gray area; it may suffice for a particular study but not for another. Several elemental determinations accompanied by errors in excess of 10 percent will tend to reduce the inferential utility of the data.

Data having moderate precision might be sufficient to identify the products of *interregional* or long distance trade, especially if different ceramic resource areas are geologically diverse. However, greater precision is useful—and often is necessary—for the characterization and discrimination of production centers involving short distances or *intraregional* exchange. As will be discussed below, higher precision should be the objective if the data are to contribute to the establishment of shared data bases.

PROCUREMENT OF ANALYTICAL SERVICES

Having discussed briefly the concepts of sensitivity, accuracy, and precision, we now can relate them to a discussion of the problems that may arise in the acquisition of analytical data. In a period of shrinking resources, spiraling costs, and limited support, archaeologists understandably are interested in minimizing analytical expenses, as are analysts (Hancock et al. 1986).

Until recently, university-based facilities and other research laboratories have been used to conduct numerous analyses, especially as techniques and applications were being developed and especially where there was a constant pool of graduate-student labor. With more demands being placed on these analytical facilities, however, research laboratories increasingly are pressed to allocate resources by some evaluatory criteria.

Under these circumstances, the contributions of energetic enthusiasts who donate free analytical services would seem to be most welcome. Too often free analytical services are dependent on access to certain instrumentation, however, and archaeologists must work with the analysts to determine that the instrumentation and precision levels are appropriate to their research questions. Shepard's admonition to archaeologists is still pertinent today: "I think the archy [archaeologist] would use analytical methods in ceramics more intelligently if he had to pay the cost" (Shepard, A. O., Letter to P. Scherer. October 2, 1958. Shepard Archives, University of Colorado, Boulder).

Analytical measurements are as demanding of interpretation as are the archaeological materials recovered through excavation. In too many cases, archaeologists have accepted analytical data without being able to interpret the nature of the data *adequately*. That is, "black-box" data have been accepted by the archaeological community on the strength of "scientific authority" alone; all data, regardless of analytical precision have been treated in subsequent statistical analyses as though they were equal in quality. If treated in this manner, archaeologists may form "groups" of seemingly related samples that relate more to analytical error than to other natural or cultural factors. By extension, "natural groups" of samples may not be recognized because of insufficient analytical precision.

To avoid such errors, archaeologists must be able to monitor the analytical process, from sampling through analysis. Although the problems discussed here relate to noncommercial as well as commercial laboratories, the low-cost, fast-turn-around service offered by commercial laboratories is being used more and more frequently by archaeologists seeking analytical alternatives. To what extent, then, can archaeologists monitor analyses purchased from commercial laboratories?

Analytical determinations with sensitivity extending down to the trace-elemental level are essential for geological exploration, several areas of the environmental sciences, and various quality-control applications. In response to the need for rapid, low-cost analyses, several analytical service companies have been formed. Some laboratories specialize in providing a range of analytical services for geological- or industrial-testing programs and combine several different analytical techniques in an analysis of a rock (or sherd) sample. A large range of elemental concentrations is determined, with laboratories often reporting as many as 40 or more elements.

Some laboratories have been created specifically to provide the geological exploration community with facilities for detecting an elemental "anomaly" above a background. Data have to be provided quickly, often while exploration teams are still in the field. A common feature shared by these laboratories is the automation of the analytical procedures in order to produce such analyses quickly. Routine analyses and rapid throughput contribute added economic benefits, that is, a low per-sample cost.

Given a cost of as little as \$25 (or less) for a sample on which a number of elemental determinations (40 or more) is made, these commercial laboratories represent a cost-effective alternative, if used critically. By taking certain precautions, archaeologists can help to ensure that the results are appropriate and can be employed in a comparative data base.

Analytical Precision

Before sending samples to any laboratory, complete information about the laboratory's analytical procedures should be gathered. Statements of precision should be based realistically on multiple samples of specimens and the analysis of a known reference material, not merely the repeated analysis of a single sample; the latter would be only an indication of instrumental stability. Based on the first author's experience in analyzing thousands of ceramic samples from different environments around the world, "exploration" packages giving elemental determinations primarily between 10 and 30 percent probably will *not* be adequate for *intra*regional comparisons. Nor will the data be of suitable quality to store in a data bank even though acceptable standardization is carried out.

Sample Preparation

In addition, find out how the samples are treated prior to analysis. For example, are they dried prior to weighing? Adsorbed water can cause proportional differences in elemental concentration of as much as 15 percent. Archaeologists should clean the samples prior to submission to remove any material (e.g., dirt, slip, paint) that might serve as a contaminant to a paste characterization. One cannot know a priori how such materials will affect the result, but one can reason that a flake of iron paint in a small sample from a kaolin-based ceramic will drastically affect the determined iron concentration. To the extent possible, variation in a data set should reflect natural and cultural factors, not sampling errors.

Likewise, contamination from the sampling equipment should be avoided, especially as trace-elemental analysis detects at levels of parts per billion. For INAA, the extraction of ceramic powder may be accomplished via an electric drill. A tungsten-carbide bit or rotary file (for use on whole vessels) can be used (Abascal-M et al. 1974; Attas et al. 1984).² An alternative method using a mounted bit made of synthetic sapphire is preferred by Perlman and Asaro (1969). If the sherd is to be crushed, as may be necessary if a large amount of material is required, agate, alumina, or synthetic sapphire mortars and pestles should be used. Even for unconsolidated clays, avoid using steel ball mills or metal sieves, both of which can contaminate the sample (see Levinson 1974:254–258).

Sample Replication

Most importantly, multiple samples taken from one or more specimens should be included. Although funding for analyses is usually a limiting factor and the inclusion of several replicate samples decreases the number of individual ceramics to be run, the archaeologist must nevertheless be aware of the quality of data being purchased. We can only restate what we hope is implicit throughout this paper: If you cannot be sure of the quality of the data being purchased, then no materials should be submitted for analysis. If complete technical information about the analysis is difficult to obtain, then the extent of agreement between the individual determinations among the replicate analyses can suggest which elements might be best to use for the purposes of characterization. For example, the lack of close agreement of some elemental determinations made from replicate analyses of white ware pottery from east-central Arizona alerted the archaeologists that the data had to be used with caution (Tuggle et al. 1982). Our review of the INAA gamma spectra revealed that those which were not in reasonably good agreement, however, were those for which the analytical precision was poor.

The practice of submitting replicate samples was shown to be cost effective in a case where information about specific analytical procedures, apart from the techniques applied, was not available. In the San Xavier Bridge Site project, Bishop (1987) was able to use the replicate ceramic samples to select a subset of elements for modeling the data. Sixteen elemental concentrations that showed reasonably close agreement were selected for data modeling from among the 52 elemental concentrations that had been provided by the laboratory.

Standards

In addition to replicate ceramic samples of unknown composition, *several* samples of well-known reference materials should be submitted, interspersed along with the other ceramic samples, and treated as unknowns within the analytical process. Use of multiple samples of a given reference material will afford an opportunity (however limited) to normalize the data to that standard even if the analytical determinations are carried out using other primary or secondary standards. While the use of reference materials will not increase the precision of the data, it will allow the researcher to assess the relative accuracy of each elemental determination.

GROWTH OF DATA BASES

Even at a relatively low cost per sample, obtaining a "sufficient number" of analyses to characterize one or more sources of ceramic production is an expensive proposition. The creation of an analytical data base, therefore, is a very reasonable way to store ceramic analyses gathered over a period of several years. Future researchers can add to these data and use the data base for both large and small scale comparisons over time and space. The desirability of having such a data base has been recognized by many individuals, among them, ceramic engineers, analysts, and archaeologists (e.g., Matson 1982:130–131; Sayre 1982:116–120; Tuggle et al. 1982:22; Whittlesey 1987:116; Yeh and Harbottle 1986).³

The need to increase the number of samples and to make them compatible with previous work is central to the effective utilization of analytical resources. This objective requires normalization of the data to a well-established and available standard reference material and requires that the data be produced within the limits of reasonable analytical precision. There is, of course, an increased cost for meeting these requirements as illustrated in the following examples.

Crown (1983) and Crown et al. (1984) carried out analyses of Hohokam pottery and clays from central Arizona using a nondestructive, qualitative or semi-quantitative, XRF technique. The analytical process was rapid. A cleaned edge or slightly ground surface was exposed to X-ray radiation and counted for a given length of time. Following background subtraction and peak integration, the relative intensities of the fluorescent spectra were used to characterize the samples (see also Olinger 1987a, 1987b, 1988).

For a single-purpose endeavor or for a cursory pilot study, this level of analysis may be quite adequate. However, it is highly system dependent. That is, if the configuration of the electronic components is modified, or should the energy of the X-ray source be changed, intralaboratory comparability will be lost. For similar reasons, data generated using other X-ray systems will not be comparable without reference to a standard material. Although these data may be stored in a data bank, without normalization, there are no replicable data. The data base can serve only as a laboratory specific reference.

During an investigation of Tikal ceramics using the XRF procedure described above, 13 control samples were prepared as fused lithium-tetraborate disks and submitted for *fully* quantitative analysis. In comparing the two techniques, Schwalbe (Culbert and Schwalbe 1987:638) pointed to four primary sources of error that he considered inherent in his first approach: counting statistical error, variations in sherd surface geometry, positioning of the samples, and basic inhomogeneities in the samples. He believed the last three equaled in magnitude the first or counting error. He estimated that the analytical precision could be substantially improved but at a cost in sample preparation and counting time of approximately two orders of magnitude. That two orders of magnitude, however, is an inexpensive price to pay to ensure that others can build on those data in subsequent investigations.⁴

The generation of data that cannot be built upon by other laboratories has other negative implications. While ceramics retrieved from ongoing projects may be readily available and plentiful, organized museum collections offer a more finite resource. Museum curators are responsible for a range of multiuser requests that at times may seem to be in conflict; they must be concerned with the use of the collections in research projects and yet limit destructive sampling to that which is minimal but warranted. Samples taken by researchers from any type of limited resource must be chosen carefully to yield the maximum information. Consideration must be given also to the long-term return rather than a short-range perspective of the immediate objective. Any analysis from the limited resource that is not in a form upon which future analyses can build, in fact, jeopardizes future archaeological ceramic research.

Ceramic compositional analysis is a powerful addition to the archaeological tool kit, but the analytical procedures and interpretations cannot be made foolproof. Ultimately, the archaeologist bears the responsibility for its effective use, enjoying the new understanding that comes from archaeologically significant interpretations and accepting the blame when analytical resources are

wasted. Attention paid to analytical sensitivity relative to the questions asked and the analytical precision at which the data are produced will contribute to the growth of commonly available data bases and provide a firmer base for archaeological interpretation of ceramic compositional data.

REFERENCES CITED

- Abascal-M, R., G. Harbottle, and E. V. Sayre
1974 Correlation Between Terra Cotta Figurines and Pottery from the Valley of Mexico and Source Clays by Activation Analysis, In *Archaeological Chemistry*, edited by C. W. Beck, pp. 81--99. Advances in Chemistry Series 138. American Chemical Society, Washington, D.C.
- Attas, M., J. M. Fossey, and L. Yaffe
1984 Corrections for Drill-bit Contamination in Sampling Ancient Pottery for Neutron Activation Analysis. *Archaeometry* 26:104-107.
- Bishop, R. L.
1987 Ceramic Paste Compositional Chemistry: Initial Observations of Variation in the Tucson Basin. In *The Archaeology of the San Xavier Bridge Site (AZ BB:13:14) Tucson Basin, Southern Arizona*, edited by J. C. Ravesloot, Appendix E, pp. 395-408. Archaeological Series No. 171. Cultural Resource Management Division, Arizona State Museum, Tucson.
- Bishop, R. L., M. J. Blackman, and J. S. Olin
1983 SARCAR: A New Archaeometric Resource. In *ICOM Committee for Conservation, 7th Triennial Meeting, Copenhagen*, edited by D. de Froment, pp. 84.8.1-2. International Council of Museums, Paris.
- Bishop, R. L., V. Canouts, S. P. De Atley, A. Qoyawayma, and C. C. W. Aikins
1988 The Formation of Ceramic Analytical Groups: Hopi Pottery Production and Exchange, A.C. 1300-1600. *Journal of Field Archaeology* 15:317-337.
- Bishop, R. L., and H. Neff
1989 Compositional Data Analysis in Archaeology. In *Archaeological Chemistry IV*, edited by R. O. Allen, pp. 57-86. Advances in Chemistry Series 220. American Chemical Society, Washington, D.C.
- Bishop, R. L., R. L. Rands, and G. R. Holley
1982 Ceramic Compositional Modeling in Archaeological Perspective. In *Advances in Archaeological Method and Theory*, vol. 5, edited by M. B. Schiffer, pp. 275-331. Academic Press, New York.
- Blackman, M. J.
1986 Precision in Routine I.N.A.A. Over a Two Year Period at the NBSR. In *NBS Reactor: Summary of Activities July 1985 Through June 1986*, edited by F. J. Shorten, pp. 122-126. NBS Technical Note 1231. U.S. Department of Commerce/National Bureau of Standards, Gaithersburg, Maryland.
- Crown, P. L.
1983 An X-ray Fluorescence Analysis of Hohokam Ceramics. In *Material Culture*, edited by L. S. Teague and P. L. Crown, pp. 277-310. Hohokam Archaeology Along the Salt-Gila Aqueduct Central Arizona Project volume VIII. Archaeological Series No. 150. Cultural Resource Management Division, Arizona State Museum, University of Arizona, Tucson.
- Crown, P. L., and R. L. Bishop
1987 Convergence in Ceramic Manufacturing Traditions in the Late Prehistoric Southwest. Paper presented at the 52nd Annual Meeting of the Society for American Archaeology, Toronto.
- Crown, P. L., A. Schwalbe, and J. R. London
1984 X-ray Fluorescence Analysis of Materials Variability in Las Colinas Ceramics. Ms. in possession of author.
- Culbert, T. P., and L. A. Schwalbe
1987 X-ray Fluorescence Survey of Tikal Ceramics. *Journal of Archaeological Science* 14:635-657.
- Deutchman, H. L.
1980 Chemical Evidence of Ceramic Exchange on Black Mesa. In *Models and Methods in Regional Exchange*, edited by R. E. Fry, pp. 119-133. SAA Papers No. 1. Society for American Archaeology, Washington, D.C.
- Earle, T. K., and J. E. Ericson
1977 Exchange Systems in Archaeological Perspective. In *Exchange Systems in Prehistory*, edited by T. K. Earle and J. E. Ericson, pp. 3-12. Academic Press, New York.
- Flanagan, F. J.
1967 U.S. Geological Survey Silicate Rock Standards. *Geochimica et Cosmochimica Acta* 31:289-308.
1969 U.S. Geological Survey Standards—II. First Compilation of Data for the New U.S.G.S. Rocks. *Geochimica et Cosmochimica Acta* 33:81.
1979 1972 Values for International Geochemical Reference Samples. *Geochimica et Cosmochimica Acta* 37:1189.
- Hancock, R. G. V., N. B. Milet, and A. J. Mills
1986 A Rapid INAA Method to Characterize Egyptian Ceramics. *Journal of Archaeological Science* 13:107-117.
- Harbottle, G.
1976 Activation Analysis in Archaeology. In *Radiochemistry: A Specialist Periodical Report*, vol. 3, edited by G. W. A. Newton, pp. 33-72. The Chemical Society, London.

- 1982a Provenience Studies Using Neutron Activation Analysis: The Role of Standardization. In *Archaeological Ceramics*, edited by J. S. Olin and A. D. Franklin, pp. 67–78. Smithsonian Press, Washington, D.C.
- 1982b Chemical Characterization in Archaeology. In *Contexts for Prehistoric Exchange*, edited by J. E. Ericson and T. K. Earle, pp. 13–52. Academic Press, New York.
- Ives, D. J.
1975 Trace Element Analyses of Archaeological Materials. *American Antiquity* 40:235–236.
- Kra, R.
1986 Standardizing Procedures for Collecting, Submitting, Recording, and Reporting Radiocarbon Samples. *Radiocarbon* 28(2A):765–775.
- Levinson, A. A.
1974 *Introduction to Exploration Geochemistry*. Applied Publishing, Maywood.
- Matson, F. R.
1982 Selection and Conservation of Study Materials and of the Data Obtained. In *Future Directions in Archaeometry*, edited by J. S. Olin, pp. 128–131. Smithsonian Institution, Washington, D. C.
- Olin, J. S., and M. J. Blackman
1989 Compositional Classification of Mexican Majolica Ceramics of the Spanish Colonial Period. In *Archaeological Chemistry IV*, edited by R. O. Allen, pp. 87–112. History of Chemistry Series 220. American Chemical Society, Washington, D.C.
- Olinger, B.
1987a Pottery Studies Using X-ray Fluorescence, part 1. An Introduction, Nambe Pueblo As an Example. *Pottery Southwest* 14(1):1–2.
1987b Pottery Studies Using X-ray Fluorescence, part 2: Evidence for Prehistoric Reoccupation of the Pajarito Plateau. *Pottery Southwest* 14(2):2–5.
1988 Pottery Studies Using X-ray Fluorescence, Part 3: The Historic Pottery of the N. Tewa. *Pottery Southwest* 15(4):1–6.
- Perlman, I., and F. Asaro
1969 Pottery Analysis by Neutron Activation. *Archaeometry* 11:21–52.
1971 Pottery Analysis by Neutron Activation. In *Science and Archaeology*, edited by R. H. Brill, pp. 55–64. M.I.T. Press, Cambridge.
- Rapp, G. R., Jr.
1985 The Provenience of Artifactual Raw Materials. In *Archaeological Geology*, edited by G. R. Rapp, Jr., and J. A. Gifford, pp. 353–374. Yale University Press, New Haven.
- Sayre, E. V.
1982 Preservation and Coordination of Archaeometric Data: The Whole Is Greater Than the Sum of Its Parts. In *Future Directions in Archaeometry*, edited by J. S. Olin, pp. 116–120. Smithsonian Institution, Washington, D.C.
- Tuggle, D. H., K. W. Kintigh, and J. J. Reid
1982 Trace-Element Analysis of White Wares. In *Ceramic Studies*, edited by J. J. Reid, pp. 22–38. *Cholla Project Archaeology*, volume 5. Archaeological Series No. 161. Cultural Resource Management Division, Arizona State Museum, University of Arizona, Tucson.
- Whittlesey, S. M.
1987 Problems of Ceramic Production and Exchange: An Overview. In *The Archaeology of the San Xavier Bridge Site (AZ BB:13:14) Tucson Basin, Southern Arizona*, edited by John C. Ravesloot, pp. 99–116. Archaeological Series No. 171, part 3. Cultural Resource Management Division, Arizona State Museum, University of Arizona, Tucson.
- Wilcock, J. D., R. L. Otlet, A. J. Walker, S. A. Charlesworth, and J. Drodge
1986 Establishment of a Working Data Base for the International Exchange of ¹⁴C Data Using Universal Transfer Formats. *Radiocarbon* 28(2A):781–787.
- Yeh, S.-J., and G. Harbottle
1986 Intercomparison of the Asaro-Perlman and Brookhaven Archaeological Ceramic Analytical Standards. *Journal of Radioanalytical and Nuclear Chemistry, Articles* 97(2):279–291.
- Yellin, J., I. Perlman, F. Asaro, H. V. Michel, and D. F. Mosier
1978 Comparison of Neutron Activation Analysis from the Lawrence Berkeley and Laboratory and the Hebrew University. *Archaeometry* 20:91–96.

NOTES

¹ Over a sufficiently long period of counting time, with a larger number of counts, the deviations from the mean more closely will approximate a normal error curve. The error is calculated from the square root of the number of counts; i.e., the square root of the number of counts divided by the number of counts and multiplied by 100. Thus a peak with only 1,000 net counts will have a minimum, nonreducible error of 3 percent built into it; if the error due to counting statistics is to be kept below 1 percent more than 10,000 counts must be accumulated.

² Tungsten-carbide drill bits and rotary files that have been used for several years and have been analyzed for

their composition and possible contaminating constituents are available from Jarvis Cutting Tool Company, Rochester, New Hampshire. For specific information, contact Ronald L. Bishop at the Conservation Analytical Laboratory.

³ The creation of the Smithsonian Archaeometric Research Collections and Records (SARCAR) at the Conservation Analytical Laboratory of the Smithsonian Institution was an explicit response to this way of thinking (Bishop et al. 1983). One function of this facility is to provide a center for archiving analytical data derived by scientific analysis of archaeological materials.

⁴ Schwalbe concurs in this assessment and states that in subsequent research programs involving archaeological ceramic analysis he will opt for the slower, fully quantitative, wavelength dispersion procedure (Schwalbe, personal communication 1988).

Received January 3, 1989; accepted June 12, 1989

AREAL DECREASE, DENSITY INCREASE, AND CIRCUMSCRIPTION: A MATHEMATICAL NOTE

Robert Bates Graber

Population density increases whenever a population grows more rapidly, or shrinks more slowly, than the area it inhabits; areal contraction therefore accelerates density increase. This consideration not only reinforces Dickson's (1987) suggestion that circumscription by anthropogenic environmental destruction contributed to the rise of some early states; it also implies that rate of density increase should be distinguished, as a motor of sociocultural evolution, from density itself. In light of this distinction the rise of the state in southwestern Iran, and occasional instances of high density among nonstate societies, are not necessarily inconsistent with population-pressure theories.

La densidad de una población aumenta cuando la población crece más rápidamente o disminuye más lentamente que el área que ésta habita; por consiguiente, la contracción del área acelera el aumento de la densidad poblacional. Esta teoría no sólo respalda la sugerencia de Dickson (1987), quien sostiene que la circunscripción mediante la destrucción antropogénica del ambiente contribuyó al florecimiento de algunos estados de la antigüedad; la teoría también implica que conviene distinguir entre la tasa del aumento de la densidad poblacional, como motor de la evolución sociocultural, y la densidad como tal. A la luz de esta distinción, el florecimiento del estado en el suroeste de Irán, y los casos de alta densidad entre algunas sociedades pre-estatales, no están necesariamente en desacuerdo con las teorías que acentúan la importancia de la presión de la población (population pressure theories).

In a valuable addendum to Carneiro's (1970) brilliant theory of political evolution, Dickson (1987) points out that environmental degradation apparently was a conspicuous feature of the evolution of several pristine states. Dickson's point indirectly suggests a quantitative response to the leading challenge to Carneiro's theory (Wright and Johnson 1975), an alternative to the qualitative response offered by Carneiro himself (Carneiro 1988).

A useful way to conceptualize environmental circumscription, social circumscription, and resource concentration is as *the totality of circumstances conducive to increase of population density rather than to areal expansion* (Graber 1988). In mathematical terms, density increase over time implies a positive average rate of change in density.

Robert Bates Graber, Division of Social Science, Northeast Missouri State University, Kirksville, MO 63501

American Antiquity, 55(3), 1990, pp. 546-549.
Copyright © 1990 by the Society for American Archaeology