Acc. Chem. Res. **2002,** *35,* 603−610

Instrumental Neutron Activation Analysis of Archaeological Ceramics: Scale and Interpretation

RONALD L. BISHOP AND
M. JAMES BLACKMAN*
*Smithsonian Center for Materials Research and Education,
Smithsonian Institution, 4210 Silver Hill Road,
Suitland, Maryland 20569*

Received July 11, 2001

ABSTRACT
Instrumental neutron activation analysis has become a standard technique for the study of the production and distributional patterns of archaeological pottery. Questions once framed within the context of long distance exchange are now focused on issues of subregional and even intrasite levels. The increasing specificity at which these questions are poised requires a high level of analytical precision as we seek to observe statistically and archaeologically significant differences among groups of pottery produced from geographically closely spaced resources or the compositional differences that arise from production behaviors of the producers of the pottery.

Introduction

The application of instrumental neutron activation analysis (INAA) to the study of archaeological ceramics began more than 4 decades ago.[1−4] Since the mid-1970s it has been the preferred analytical technique for addressing archaeological questions pertaining to the procurement and use of raw materials and trade or exchange of finished goods. No other technique offers a comparable level of great sensitivity and high precision combined with the ease of sample preparation. This Account examines issues pertaining to the scale at which INAA is used in archaeological application. In so doing, it emphasizes the role of analytical precision, which must be achieved for the spatial resolution of raw material resources and specific production recipes used in the production of pottery. As the objectives of specific research problems are addressed, the data eventually find their way into large databases, the use of which requires that the high analytical precision be sustainable over many years.

Background

The analytical technique is based on the interaction of neutrons with the nucleus of atoms to produce radioactive isotopes, the quantity of which can be used to determine the elemental concentration in a sample. When neutrons interact with the nuclei of atoms, radioactive isotopes may be formed through neutron capture, the type of interaction depending upon the energy of the neutron. The newly formed isotopes release energy through several means, including the emission of electromagnetic energy in the form of γ-rays. γ-Ray counts are most frequently used with comparator standards of certified NIST reference materials to quantify the elemental concentrations in an unknown sample, although the k_0 method is employed in some European and South American facilities.[5−8] These data can then be used to calculate intesample compositional relationships and modeled to infer the *source* from which the cultural materials were produced.

We became involved with archaeological applications of INAA in the early 1970s, at a time when the general analytical procedures had been roughed out, electronic instrumentation began to approach stability, and computer mainframes permitted serious data crunching. Protocols remained to be optimized for specific laboratory situations, but the primary effort was shifting from an overriding concern with technique development to that of application. Increasingly, attention was given to the examination of the underlying natural and cultural sources of elemental variation that could be encountered in data matrixes of archaeological pottery and how that information could be used to provide a more accurate interpretation of the past.[9,10]

While details of the analytical procedure have become well-understood, the use of the derived data to explain the archaeological record has remained complex. Part of the reason for this complexity is that investigators are limited by not being able to directly view the processes responsible for specific occurrences of ceramic distributions. They are forced, therefore, to explain the patterns of ceramic distribution with only limited data reflecting the behavioral actions that took place in the past. Data derived from the study of archaeological pottery, whether from INAA or other techniques, regardless of how sensitive, accurate, or precise the analyses were, may well be meaningless unless factors that contribute to the observed compositional variation in the pottery are considered.[11] In general, pottery is a multicomponent system, commonly composed of clay that has been procured, processed (e.g., sorting, screening, and levigation[12]), and often altered though the addition of other materials (e.g., raw

---

Ronald L. Bishop was born in San Francisco, CA, in 1942. He studied chemistry at San Jose State University and anthropology at San Francisco State University. Using data-derived INAA that he carried out at Brookhaven National Laboratory, he received a Ph.D. in anthropology, with a speciality in Maya archaeology, from Southern Illinois University at Carbondale. He spent several years working on postdoctoral projects, applying chemical analysis to archeological questions involving several archaeological materials, but especially ceramics. In 1983 he joined the Smithsonian Institution as a Research Archaeologist and has served since 1994 as the Coordinator of Research for the Smithsonian Center for Materials Research and Education.

M. James Blackman was born in Youngstown, OH, in 1943. He received his B.A. in chemistry (1964) and his M.S. in Geology (1969) from Miami University in Oxford, OH. He received his Ph.D. in Mineralogy from The Ohio State University, Columbus, OH (1975). He has conducted archaeological and geological fieldwork in Iran, Syria, Turkey, and Mexico. He joined the Smithsonian Institution in 1976 and is currently a Senior Research Chemist at the Smithsonian Center for Research and Education, Smithsonian Institution, where he runs the Smithsonian's Nuclear Laboratory for Archaeological Research at the National Institute of Standards and Technology in Gaithersburg, MD. Research projects have included the analysis of wide range of cultural materials, including obsidian, chert, steatite, and pottery.

10.1021/ar000199k CCC: $22.00

or fired clay, sands, volcanic shards, dung[13]) to modify the working, firing, and use properties. The influence of behavior choices made in the past frequently prevents an investigator from being able to “match” pottery with a specific geological clay source. It is more common, therefore, to establish compositional groups of ceramics that are inferred to be representative of geographically differentiable resources.

Compositional Research: The Question of Scale

The archaeological application of INAA is essentially spacial in nature, for one seeks to distinguish among the products made from different sources of raw materials to establish the specific clay sources from which the pottery was made. It proceeds under two general premises: the first holds that it is possible to characterize an archaeological object or source material according to some set of objectively determined parameters, and the second, the so-called “Provenience postulate”,[14] holds that when using an adequately sensitive analytical technique, identifiable chemical differences may be observed between raw material sources and that variation within a source will be less than the variation among sources. Holding others factors constant, it follows, therefore, that artifacts manufactured from a particular source will be more similar to others produced from that source than they will be to objects produced from other sources. Both of these premises revolve about our ability to in some way characterize a “source.” Yet what constitutes a “source” is a variably defined construct of scale that may be well removed from “on-the-ground” reality.

The simplest delimiting of a raw material source that was exploited in the past can be illustrated by a characterization of a specific obsidian flow or a particular clay deposit. These might be considered “point sources” that can be differentiated from other similarly defined point sources. More generalized, and hence more difficult to delimit geographically, are the compositional patterns for pottery drawn from several sites within a region. Compositional differentiation might be focused on the level of a particular site, on several sites within a *sub*region (site cluster), or extended to a regional level, which might encompass hundreds of square kilometers. A focus on the latter might lead to the selection of one area within the region over others for more detailed study. When more than a single, sampled source is involved, characterization becomes less direct, with attribution of manufacturing loci resting on the validity of the archaeological criterion of abundance, as evaluated within a chronological perspective. For example, as a first approximation, the pottery found to be in abundance at a site is more likely to be of “local” production than is the pottery that is sparsely represented. If the abundant pottery of a given archaeological period is found to have a characteristic composition that is also present in the abundant pottery of earlier and successive periods, the assumption of locally available resources is strengthened. Note that here no actual source material is analyzed directly but is inferentially reflected by the composition of the artifacts. The geographical extent of the source or sources remains, of course, unknown but may be geographically circumscribed by similar characterization of the pottery from neighboring sites.

Unfortunately, we can never know the parameters of the population from which the sample was drawn and we are never sure of the adequacy of our sample. This has the effect of requiring that the data derived from the sample be modeled rather than using the sample to model the underlying processes responsible for the ceramic distributions. Since the models that are derived to account for the archaeological record constitute a synthesis of empirical reality augmented by the liberal use of a fertile imagination, the chemical data generally are screened for some pattern that yields a positive correlation with other types of archaeological data.

Space, Scale, and Precision

If space is a primary dimension of variation within which patterns pertaining to ceramic production and distribution are sought, then attention must be given to consideration of the concept of scale. Scale refers to the extent of sampling and the physical and cultural resolution that is required to address a given research question; it is a fit between analytical precision, data analysis, and humanistic considerations. When evidence of long distance trade is required, for example, between the Indus valley and the Oman Peninsula or Central Mexico and the Maya region, the likelihood of significant differences in local raw materials may make for relatively unambiguous separation of compositional profiles. Alternatively, when differentiation is sought among potentially closely spaced production centers or when evidence of workshop production is the subject of interest, the requirements of the investigation become more rigorous. Sampling must be more intensive, variations as a function of small differences in the amount, kinds, or sorting of temper become important, and the control of temporal variation takes on more significance. As important as the concept of scale is to a successful INAA-based study of archaeological ceramics, it is not often the subject of specific discussion.

Below, following a presentation of analytical precision that has been maintained over more than 20 years, we offer examples of our research involving the application of INAA to questions of ceramic production and distribution to illustrate the role of scale on the archaeological interpretation. While not initially formulated as such, these studies also could be used to show the evolution of the use of INAA in archaeology from that of just demonstrating the long distance movement of pottery toward increased incorporation of analytical data to address social, economic, and political processes that might account for the distribution of specific pottery. First, however, we comment on aspects of INAA that we follow for the long-term maintenance of high analytical precision, which is essential for the generation of large data sets.

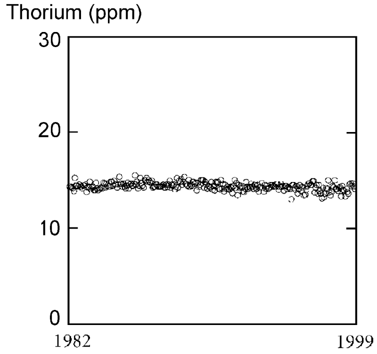

FIGURE 1. Determination of thorium concentration over time in NIST SRM679 as check standard.

The analytical protocol followed at the Smithsonian Center for Materials Research and Education's Nuclear Laboratory for Archaeological Research, maintained at the National Institute of Standards and Technology in Maryland, is designed to optimize sample throughput, maximize the number of elemental constituents quantified, and maintain a sufficiently high level of analytical precision to address archaeological questions requiring fine discrimination among raw material sources. A comparator method of quantification is utilized, with NIST Standard Reference Material 1633 (Coal Fly Ash) as the standard. Check standards are included with each irradiation to monitor precision, accuracy, and long-term analytical stability. The check standards analyzed between 1982 and 1999 consisted of 311 analyses of NIST SRM 679 Brick Clay, 213 analyses of a 1970s bag of Ohio Red art clay, and 124 analyses of a different shipment of Ohio Red art clay obtained after a shift of mining location in the early 1980s. Complete experimental procedures are given elsewhere.[15]

As mentioned above, many projects rely on large databases built up over a number of years. For samples analyzed in 2001 to be confidently compared with data collected, in say, 1985, and for subtle differences in elemental concentrations to reliably be attributed to differences in ceramic composition, the analytical procedure must be constantly monitored using check standards. Figure 1 shows a plot of concentration vs time for one element, thorium, in the NIST SRM679 check standard. As can be seen in the plot, the thorium concentration line remains flat within a coefficient of variation of 2.7% over the entire 18-year period (as is true for an additional 23 elements), indicating no systematic shift over time. Table 1 presents the descriptive statistics for all the elements routinely quantified in SRM679. It should be noted that the coefficients of variation for the elements reflect all systematic and random errors introduced over the 18-year period, including sample inhomogeniety. This not withstanding, 18 elements are quantified to 8% or better, with 12 of those elements better than 4%. The column headed NCV (normalized coefficient of variation) gives a better idea of the stability of the analytical system over time. The NCV. is the coefficient of variation with the greatest source of error in the analysis, the γ-ray counting statistics, subtracted out. The NCV values for SRM679 indicate that all sources of error other that counting statistics are less than 4% in all but three elements (zinc, antimony, and terbium). Taken together, these data demonstrate the confidence we have in using all analyses, whenever undertaken, in our archaeological interpretations. The data obtained from the analyses of the Ohio Red art clay provided comparable levels of analytical precision as that obtained with SRM 679.

Ceramic Production at the Site Level

In many archaeological investigations of ceramic production the samples selected, even from sealed deposits, may represent manufacturing events extending over several years to a hundred or more. Thus, assessment of variation at a single point of time in the past is rare. Nonetheless, archaeologists are interested in measures of variation in different parameters for their potential insight regarding how production was organized. A reduction in heterogeneity in physical and stylistic features is frequently taken as an indication of increased specialization of production, an important factor in the evolution of social complexity.[16−19] An adequate understanding of the relationship between compositional homogeneity and specialization, however, remains elusive.[20] Any consideration of chemical variation in pottery must include a combination of natural and analytical as well as cultural influences. One opportunity to consider the chemical variation within pottery produced in a single event, and to gain enhanced understanding of the contribution to the data from analytical errors, was offered by the analysis of a fused stack of ceramic wasters that were recovered from the site of Tell Leilan in modern Syria.

Tell Leilan is located on fertile plain near the headwaters of a tributary of the Habur river in northeast Syria. By the third millennium B.C., Leilan had become one of the largest urban centers in northern Mesopotania.[21] Among the common pottery recovered from the site were fine ware bowls produced in a distinctive open-rim, flat-based form. The abundance of this pottery at Tell Leilan and other sites in the region evidences what must have been a thriving potting industry.[22] The bowls are characterized as consisting of a uniform fine-grained greenish calcareous matrix. A survey of the locally available clays suggests that levigation was used to produce the fine, uniform qualities of the paste. Formed and dried pieces were stacked together without spacers to heights of more than a meter and kiln fired in a reducing atmosphere, to high temperatures (950−1050° C). While the reduction firing lowered the temperature at which vitrification occurs, producing the desired hard, dense ceramic body, it also resulted in occasional overfiring, fusing the stacked pieces. A portion of one of these fused stacks, (Figure 2.), consisting of 27 whole bowls, was selected for chemical analysis to address issues pertaining to the amount of variability within these specialist-produced ceramics and how that variability compares to the overall range of variation that is observed in the compositional data for this *same* type of bowl, considered at the site level.

Table 1. Elemental Composition of NIST SRM 679 (Brick Clay) Compared to Leilan Fine Ware Stacked Wasters and Open Simple-Rim Greenish Fine Ware Bowls from Leilan (Operation 4)

	SRM 679 brick clay ($n = 311$)			waster stack ($n = 18$)			fine ware: oper 4 ($n = 20$)		
element	mean	CV (%)	NCV (%)	mean	CV (%)	NCV (%)	mean	CV (%)	NCV (%)
Na (%)	0.136	2.2	1.6	0.585	2.2	1.8	0.676	8.5	8.1
K (%)	2.30	5.3	2.3	1.57	5.3	0.7	1.62	8.7	4.1
Rb (ppm)	218.	7.7	4.0	89.0	4.3	1.0	79.5	13.3	8.0
Cs (ppm)	9.66	2.4	0.7	4.47	3.0	0.6	4.08	15.1	12.7
Ca (%)	nd			12.5	4.3	4.6	13.3	12.0	3.6
Sr (ppm)	nd			424	10.9	0.3	660	20.0	8.8
Ba (ppm)	473	12.2	2.2	424	17.1	2.7	380	17.0	2.3
Sc (ppm)	23.0	1.7	1.6	17.3	1.3	1.2	16.7	6.1	6.0
Cr (ppm)	108	3.1	2.1	335	2.3	1.7	349	5.5	4.9
Fe (%)	9.03	3.0	2.8	5.19	1.2	1.0	5.06	4.9	4.7
Co (ppm)	26.7	2.0	1.5	31.2	1.3	0.9	30.9	6.4	6.0
Zn (ppm)	129.	10.6	8.6	114	2.3	0.3	101	9.0	7.0
As (ppm)	10.0	5.4	1.9	10.1	10.6	7.1	7.20	33.0	29.5
Sb (ppm)	0.982	16.8	8.4	0.936	7.6	0.1	0.869	12.0	4.3
La (ppm)	56.4	1.6	1.3	36.8	1.2	0.8	36.0	5.3	4.9
Ce (ppm)	103	2.4	1.9	68.9	1.4	0.8	67.9	6.8	6.2
Sm (ppm)	9.16	2.5	2.2	6.19	1.9	1.4	6.07	4.3	3.8
Eu (ppm)	1.69	3.0	1.9	1.35	1.3	0.1	1.32	5.9	4.7
Tb (ppm)	1.21	13.8	7.0	0.942	7.9	0.4	0.843	11.7	4.1
Yb (ppm)	4.11	5.3	2.1	3.14	4.9	1.3	3.01	6.7	3.1
Lu (ppm)	0.615	6.9	2.4	0.473	6.1	0.8	1.452	9.6	4.3
Hf (ppm)	4.57	4.0	2.2	5.64	1.9	0.5	5.93	4.5	3.1
Ta (ppm)	1.24	7.2	2.5	1.18	4.6	0.3	1.09	16.5	4.6
Th (ppm)	14.3	2.7	2.0	9.50	1.3	0.4	9.30	6.5	5.6
U (ppm)	2.41	15.3	3.8	1.92	4.0	1.9	1.90	21.3	9.8

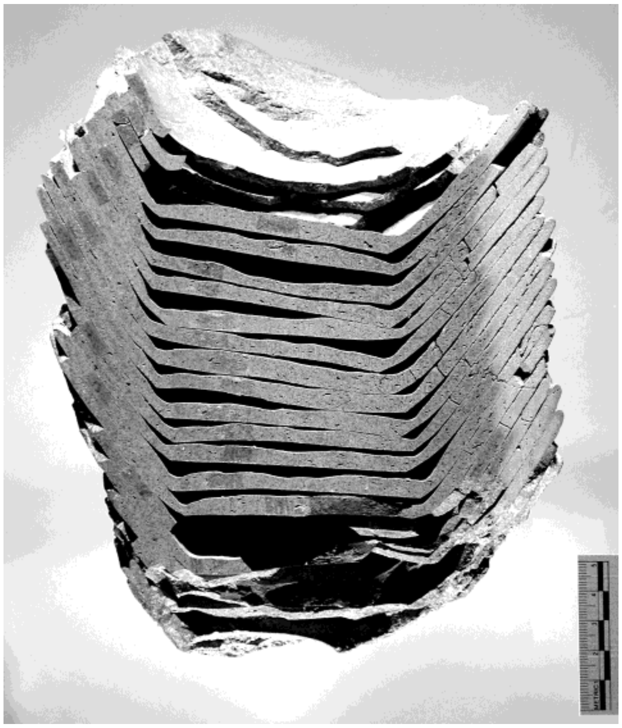

FIGURE 2. Fused waster stack of Leilan fine ware pottery, sectioned to show stacking of bowls.

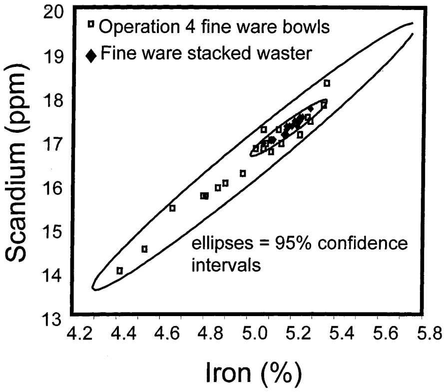

FIGURE 3. Iron–scandium plot of waster bowls compared to the fine wares of operation 4.

Eighteen of the stacked bowls were subject to chemical analysis, as were 20 stylistically similar fine paste bowls recovered from domestic contexts (operation 4), representing production over about a 100-year period.[23]

The data for these two groups, along with SRM679 for comparison, are shown in Table 1. When the normalized coefficients of variation are examined for the fine ware stacked waster group, only a single element (arsenic) has a NCV of greater than 4%. This may be explained by volatilization during firing. Of the remaining 24 elements, the vast majority have NCVs of less than 2%. Comparison with the NCVs for the check standard shows that the fine ware stacked wasters are considerably more homogeneous, no doubt due in part to the waster samples being run in only two irradiations. Their extreme homogeneity strongly suggests that they were made from a single batch of carefully prepared clay. Examination of the data for the fine ware bowl sherds from domestic refuse contexts at operation 4 shows 3–5 times greater variation when compared to fine ware wasters. Figure 3, a plot of iron vs scandium for these two groups, clearly demonstrates that the waster stack is a subset of the operation 4 ceramics. The added variation in operation 4 ceramics was introduced through time by the specialist potters using slightly different raw material sources and clay preparation techniques.

FIGURE 4. An example of Hopi Sikyatki Polychrome.

Ceramic Production at the Intraregional Level

More than 200 years prior to Spanish contact, the Hopi Indians manufactured Sikyatki Polychrome, a distinctive ceramic that was outstanding in terms of its yellow color, form, and boldly painted designs (Figure 4). Disease, turmoil, and population decline followed the Spanish arrival in 1540 A.D. Many Hopi died, while others fled the homeland in the mesas of northeastern Arizona for the Rio Grande valley of New Mexico. After the pueblo revolt of 1680, when the Spaniards were cast out, Hopi refugees returned to the Hopi mesas and with them came Rio Grande and Spanish inspired ideas of ceramic form, finish, and decoration. The knowledge of their earlier vessel forming and finish technology, a high point of Native American craft achievement, had been lost.

In the 1300s, as today, the Hopi lived in villages at the base or top of the four mesas that are part of the southward mass of Black Mesa (Figure 5). Sikyatki Polychrome was presumed to have been produced in the villages on the mesas. It has been recovered from locations as far away as the Plains states to the east and California to the west. How was the production of Sikyatki and Jeddito pottery organized? At which villages was it made? What were the patterns of intervillage interaction that one can reconstruct using ceramic evidence? These are just a few of the questions that are of interest to archaeologists working in the US southwest.

The smaller mesas at the southern edge of Black Mesa are a dissected aggregate of clay deposits overlaying interbedded sandstones and shales of the Upper Cretaceous period. Clays occur as lenses, extending for miles along mesa exposures, or as "pods" of one to several meters in diameter. Since they are derived from relatively the same parent materials, the clays tend to be mineralogically and chemically similar. The initial research plan hoped to be able to differentiate among the villages located on different mesas with very little expectation that sufficient compositional differences would be detected to allow distinction among the villages settled along a single mesa. The cultural and technological conditions, however, combine to favor the fine level of distinction. The pottery was made from kaolin clays without addition of nonplastic components (e.g., sand) to the paste. Further, recognizable combinations of particular design motifs suggest that the pottery was possibly produced by social groups, some of which may have been kin or workshop-based.

Neutron activation analysis, involving more than 1600 analyses of bowls and jars, has been carried out.[24] This included samples of more than 700 whole vessels from many different museum collections. The resulting data permitted the identification of groups of pottery that represent production at separate villages (intraregional) and, in some cases, allowed differentiation at the intravillage scale. These compositional differences are especially apparent for the villages located along the edge of Antelope Mesa. Several compositional groups have been identified through the use of multivariate cluster analysis followed by evaluation of the resulting groups by comparing individual sample distances from its assigned group's multivariate centroid. We can illustrate the observed tendencies for site-based separation by plotting the representative groups relative to their values of thorium

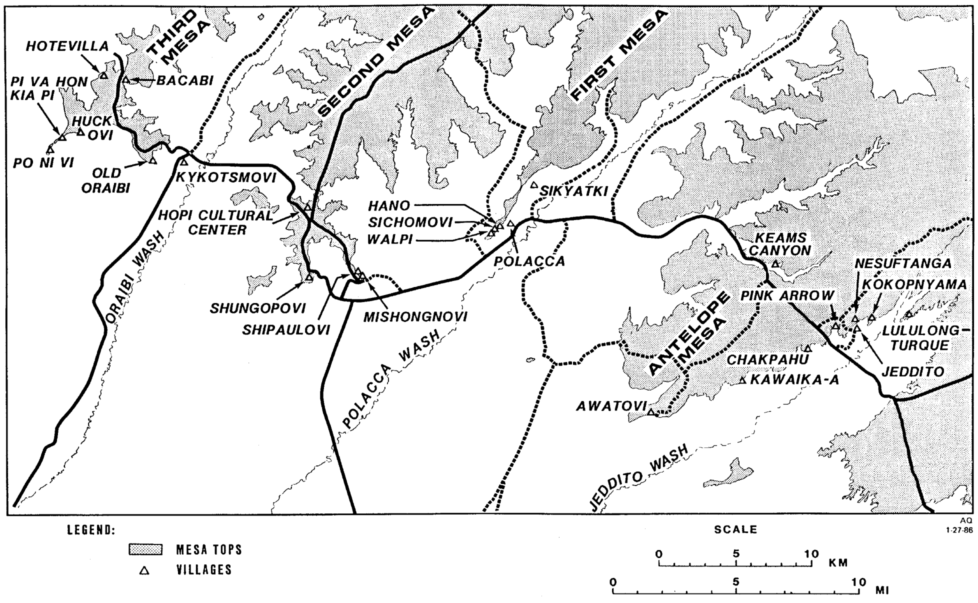

FIGURE 5. Villages on the Hopi Mesas of northeastern Arizona.

Table 2. Mean Compositions for Hopi Pottery Groups Shown in Figure 5

	Awatovi ($n = 94$)		Kawaika-a group 1 ($n = 37$)		Chakpahu ($n = 10$)		Kokop-Lulu ($n = 19$)		Sikyatki ($n = 53$)	
element	mean	CV (%)	mean	CV (%)	mean	CV (%)	mean	CV (%)	mean	CV (%)
K (%)	1.95	66	2.32	13	1.64	37	1.12	15	0.72	60
Rb (ppm)	150	158	165	15	142.	8	98.9	24	85.0	24
Cs (ppm)	9.56	18	8.75	13	10.9	8	8.68	16	8.20	20
Sc (ppm)	20.9	8	17.2	9	20.9	10	16.8	11	11.8	12
Cr (ppm)	58.9	9	50.5	10	76.8	19	50.1	11	48.2	12
Fe (%)	1.81	16	1.40	21	1.91	13	2.47	12	1.78	13
Sb (ppm)	0.57	57	0.73	25	0.95	37	1.06	17	0.70	41
La (ppm)	178.	17	128	6	94.8	15	60.4	27	8.20	20
Ce (ppm)	330	15	237	7	169	14	111	31	63.5	20
Sm (ppm)	21.8	18	15.5	7	60.7	59	7.54	31	4.54	44
Eu (ppm)	3.30	18	2.37	7	2.06	14	1.20	30	0.61	25
Yb (ppm)	8.09	24	7.21	10	6.23	13	4.33	16	4.45	23
Lu (ppm)	1.03	30	0.95	12	0.87	16	0.59	14	0.64	28
Hf (ppm)	10.7	22	15.1	9	11.0	20	9.44	23	14.2	27
Ta (ppm)	3.92	12	4.34	9	2.83	12	3.07	20	3.86	17
Th (ppm)	60.0	1	50.4	8	38.5	03	41.6	13	29.1	16

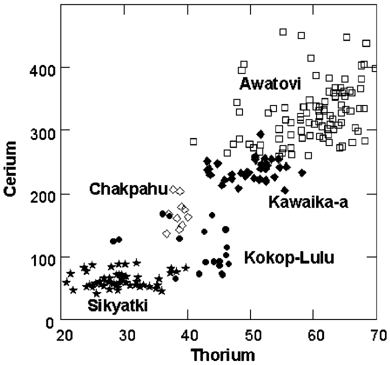

FIGURE 6. Representative groups from Antelope Mesa and First Mesa illustrating the tendency toward site-specific compositional variation in a thorium−cerium bivariate plot.

and cerium (Figure 6). Distinguishable compositions can be recognized for pottery from Awatovi, Kawaika-a, and Chakpahu and the sites of Kokopnyama and Lululongturque (the latter two sites are noted as "Kokop-Lulu; Table 2). These compositional reference groups represent difference among the ceramics produced at villages, some of which are separated by less than 8 km. Given the relative homogeneity of the available resources, the ability to observe the compositional differences among the villages studied would have been difficult, if not impossible, without the use of an analytical technique that combined high sensitivity and precision with the capacity for high sample throughput.

Ceramic Production at the Regional Level

The term "Greater Nicoya" is used by archaeologists to indicate commonality within the archaeological materials of northwestern Costa Rica and southwestern Nicaragua. Strongly influencing the geographic delineation of the area were the shared ceramic distributional patterns with their similar forms, decorative techniques, and painted representations.[25] As a geographic entity, it is traditionally treated as beginning somewhere south of the attenuated Maya area to the north, north of "high culture" areas farther south, and east of whatever else was happening in the rest of Nicaragua and Costa Rica. Within Greater Nicoya, with its common archaeological traits, continuing archaeological research has resulted in the recognition of a northern (Nicaragua) and southern (Costa Rica) sector defined by the perceived differences in settlement and subsistence patterns and the distribution of obsidian, jade, and certain ceramic products.[26] Many archaeological questions relate to patterns of production and distribution of pottery within this region and how these patterns changed as a reflection of social or economic realignments during different archaeological periods. To address some of these questions, a study of the pottery was undertaken using INAA. A database consisting of more than 1200 ceramic samples was collected.[27] Our questions were cast broadly. For example, is there compositional homogeneity observable within the samples of a given type of pottery that might suggest production and subsequent trade from a single production area of unknown size to other regions?

Using statistical procedures to model the analytical data, 36 groups of samples were formed that were internally relatively homogeneous in composition. Several of the groups contained only a few members, whereas others were made up of a sufficient number of samples to permit evaluation by multivariate statistics that consider not only the distance between samples in the multivariate space but also the pattern of covariation among the elements. Ten groups carried the dominant patterns of chemical variation for the Greater Nicoya analyzed pottery (Table 3). These groups contained over half of the specimens and represent the major ceramic types of the region. An example of the group variation is shown in Figure 7, relative to the axes obtained from a discriminant analysis of the analytical data. These groups were found to covary strongly with the ceramic typology and to reflect a division between the northern and southern sector compositions. Using both the information concerning the archaeological distribution of the pottery and the available geological information, these groups can be attributed to broadly defined areas of the Greater Nicoya region.

The chemical data permits various kinds of archaeological information to be seen in more clearly defined spatial perspective, one aspect of which is the surface slip color. While there appears to be a general regional sharing

Table 3. Mean Compositions for Major Reference Groups of Greater Nicoya Pottery[a]

	Ca (%)		Sc (ppm)		Cr (ppm)		Fe (%)		Co (ppm)		Rb (ppm)		Cs (ppm)		Ba (%)	
group	mean	CV (%)	mean	CV (%)	mean	CV (%)	mean	CV (%)	mean	CV (%)	mean	CV (%)	mean	CV (%)	mean	CV (%)
GN01 $n = 64$	3.12	19	24.8	9	68.4	23	6.40	7	20.8	39	35.5	39	1.10	52	0.091	52
GN04 $n = 122$	2.54	26	31.0	9	127.	18	7.16	8	25.6	8	35.2	49	1.21	46	0.082	52
GN05 $n = 46$	2.31	43	23.6	13	81.7	32	5.65	9	20.0	24	36.0	28	1.08	32	0.104	50
GN11 $n = 132$	2.61	31	23.4	11	12.4	38	6.28	9	13.6	35	38.5	41	1.37	26	0.097	38
GN12 $n = 50$	2.16	21	21.9	9	17.5	24	5.58	10	17.9	31	61.0	37	1.19	28	0.117	29
GN14 $n = 51$	2.12	33	17.8	24	17.3	25	4.65	17	14.9	15	34.4	34	1.23	40	0.101	38
GN15 $n = 49$	1.64	18	17.1	10	22.0	23	4.20	10	16.7	29	70.6	16	2.54	29	0.101	23
GN22 $n = 28$	2.65	32	33.3	8	20.6	17	9.44	13	24.9	47	37.2	64	8.81	41	0.084	43
GN23 $n = 66$	3.04	37	33.4	13	20.6	31	9.82	13	37.7	51	44.7	73	0.90	46	0.103	40
GN24 $n = 19$	2.60	61	23.3	10	10.5	41	6.85	10	16.1	42	52.7	46	0.79	69	0.137	30

group	La (ppm)		Ce (ppm)		Sm (ppm)		Eu (ppm)		Yb (ppm)		Lu (ppm)		Hf (ppm)		Th (ppm)	
GN01	14.8	12	24.7	27	4.2	25	1.19	11	2.66	12	0.392	13	2.90	8	1.82	12
GN04	11.6	12	19.3	24	3.5	17	1.09	9	2.456	14	0.375	15	2.99	12	1.60	17
GN05	13.6	24	24.9	28	3.5	35	0.77	22	1.82	21	0.267	21	3.78	14	3.04	16
GN11	14.4	13	21.8	30	4.4	18	1.25	10	2.98	12	0.442	15	4.79	9	3.19	11
GN12	16.0	14	33.1	17	4.7	29	1.03	16	3.14	13	0.463	14	5.78	8	3.76	9
GN14	23.1	21	35.7	33	4.3	28	1.15	17	2.20	28	0.346	17	4.40	16	5.11	21
GN15	16.3	7	32.4	33	4.7	12	1.03	11	2.88	12	0.445	16	4.51	15	3.99	9
GN22	19.8	26	32.5	37	3.4	26	0.82	20	1.60	23	0.290	19	6.15	9	4.88	8
GN23	28.3	21	61.8	39	5.8	28	1.41	21	2.62	19	0.414	25	6.55	12	5.08	14
GN24	33.5	25	54.9	26	5.8	24	1.32	30	2.69	22	0.422	26	7.16	12	5.87	15

[a] Number in parenthesis is one standard deviation expressed as a percentage of the mean.

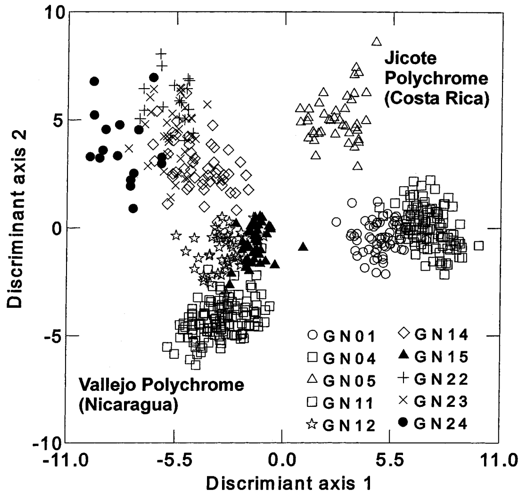

FIGURE 7. Major reference groups for Greater Nicoya pottery.

of certain design motifs, a tan or salmon slip color (e.g., Jicote Polychrome, Figure 7) is characteristic of pottery found south of the modern Costa Rican–Nicaraguan border. In contrast, white slip pottery (e.g., Vallejo Polychrome, Figure 7) is common north of the border and has been chemically determined to have been produced largely in the Rivas Peninsula of Nicaragua. The reasons for separate ceramic traditions in adjacent regions that are differentiated by slip color are unknown. Obviously cultural rather than natural factors are responsible. From a social perspective, the pattern is of great significance as the white-slipped northern types are found far more abundantly in the southern sector than the reverse, and often in high status burials. Was this an indication of some form of copying where groups in the southern sector imported white slipped pottery from the north and imitated their designs on locally produced ceramics? Apparently not. A structural analysis of stylistic features, including motifs and band sequences, indicated that the potters in the south were not imitating their northern neighbors but were working with a southern tradition that drew on the same regional influences as the north.[28]

These parallel traditions may be explained in part by the differential acceptance of Mesoamerican influenced symbolism from far to the north of Greater Nicoya. The northern sector pottery appears to have embraced a more elaborated symbol set than did the south. The occurrence of white slipped pottery in the south could have been the result of traders bringing northern goods. An alternative possibility might be that northern populations moved slowly south, from the fertile lands of the Rivas Peninsula, into a similarly fertile Tempisque Valley. Other possibilities must also be considered. Clearly, however, the chemical data have sharpened the archaeological appreciation of the importance of subregional differences in ceramic production and the social and cultural information that it carries in Greater Nicoya.

Conclusions

Although the above examples are but briefly described, they serve to illustrate some of the varying scales at which

INAA data are used to develop and strengthen archaeological inference regarding social and cultural processes. Ever more demanding questions can be formed. What is clear is that, given all uncontrollable aspects involved in the chemical characterization of archaeological ceramics, close attention must be given to maintaining analytical precision sufficiently high to permit the merger of large data sets produced over long periods of time if one is to have a reasonable expectation of observing differences among archaeological ceramics that reflect both natural and cultural processes at varying scales of consideration.

References

(1) Sayre, E. V.; Dodson, R. W. Neutron Activation Study of Mediterranean Potsherds. *Am. J. Archaeol.* **1957**, *61*, 35–41.

(2) Sayre, E. V.; Murrenhoff, A.; Weick, C. F. The Nondestructive Analysis of Ancient Potsherds Through Neutron Activation. *Brookhaven National Laboratory Report 508*; New York, 1958; pp 1–15.

(3) Perlman, I.; Asaro, F. Pottery Analysis by Neutron Activation. *Archaeometry* **1969**, *11*, 21–52.

(4) Perlman, I.; Asaro, F. In *Science and Archaeology*; Brill, R. H., Ed.; MIT Press: Cambridge, **1971**, 182–195.

(5) Glascock, M. D. Nuclear Reaction Chemical Analysis: Prompt and Delayed Measurement. In *Chemical Analysis by Nuclear Methods*; Alfassi, Z. B., Ed.; John Wiley & Sons: New York, 1994; pp 77–99.

(6) Glascock, M. D. Activation Analysis. In *Instrumental Multielement Chemical Analysis*; Alfassi, Z. B., Ed.; Kluwer Academic Publishers Groups: Dordrecht, Netherlands, 1998; pp 93–150.

(7) Landsberger, S. A. Delayed Instrumental Neutron Activation Analysis. In *Chemical Analysis by Nuclear Methods*; Alfassi, Z. B., Ed.; John Wiley & Sons: New York, 1994; pp 121–142.

(8) Neff, H. Neutron Activation Analysis for Provenance Determination in Archaeology. In *Modern Analytical Methods in Art and Archaeology*; Ciliberto, E., Spoto, G., Eds.; John Wiley & Sons: New York, 2000; pp 81–134.

(9) Bishop, R.; Rands, R. L.; Holley, G. R. Compositional Analysis in Archaeological Perspective. In *Advances in Archaeological Method and Theory*; Schiffer, M. B., Ed.; Academic Press: New York, 1982; Vol. 5, pp 275–331.

(10) Beaudry, M. P. New World Paste Compositional Investigations. In *The Ceramic Legacy of Anna O. Shepard*; Bishop, R. L., Lange, F. W., Eds.; University of Colorado Press: Niwot, 1991; pp 224–256.

(11) Bishop, R. L. Aspects of Compositional Modeling. In *Models and Methods in Regional Exchange*; Fry, R., Ed.; SAA Papers No. 1, Society for American Archaeology: Washington, 1980; pp 47–66.

(12) Blackman, M. J. The Effect of Human Size Sorting on the Mineralogy and Chemistry of Ceramic Clays. In *Chemical Characterization of Ceramic Pastes in Archaeology*; Neff, H., Ed.; Prehistory Press: Madison, 1992; pp 113–124.

(13) Neff, H.; Bishop, R. L.; Sayre, E. V. A Simulation Approach to the Problem of Tempering in Compositional Studies of Archaeological Ceramics. *J. Archaeol. Sci.* **1988**, *15*, 159–172.

(14) Weigend, P.; Harbottle, G.; Sayre, E V. Turquoise Sources and Source Analysis. In *Exchange Systems in Prehistory*; Earle, T. K., Ericson, J. E., Eds.; Academic Press: New York, 1977; pp 15–34.

(15) Blackman, M. J. Precision in Routine INAA Over a Two-year Period at the NBSR. In *NBS Reactor: Summary of Activities July 1985 through June 1986*; Shorten, F. J., Ed.; NBS Technical Note 1231, U.S. Department of Commerce, National Bureau of Standards, U.S. Government Printing Office: Washington, 1986; pp 122–126.

(16) Balfet, H. Ethnographical Observations in North Africa and Archaeological Interpretation: The Pottery of the Maghreb. In *Ceramics and Man*; Matson, F. R., Ed.; Viking Fund Publication in Anthropology No. 41, New York, 1965; pp 161–177.

(17) Feinman, G.; Kowalewski, S.; Blanton, R. Modeling Ceramic Production and Organizational Change in the Pre-Hispanic Valley of Oaxaca, Mexico. In *The Many Dimensions of Pottery*; Van der Leeuw, S, Pritchard, A. C., Eds.; Albert Egges van Giffen Instituut voor Prae- en Protohistorie, University of Amsterdam, 1984; pp 297–337.

(18) Rice, P. Evolution of Specialized Pottery Production: A Trial Model. *Curr. Anthropol.* **1981**, *22*, 219–240.

(19) Sinopoli, C. The Organization of Craft Production at Vijayanagara, South India. *Am. Anthropol.* **1988**, *90*, 580–597.

(20) Arnold, D. E. Does the Standardization of Ceramic Pastes Really Mean Specialization? *J. Anthropol. Method Theory* **2000**, *7*, 333–375.

(21) Weiss, H. P.; Akkermans, P.; Stein, G.; Parayre, D.; Whiting, R. 1985 Excavations at Tell Leilan, Syria. *Am. J. Archeol.* **1990**, *94*, 529–581.

(22) Stein, G. S. and Blackman, M. J. The Organizational Context of Specialized Craft Production in Early Mesopotamian States. In *Research in Economic Anthropology*; Isaac, B., Ed.; JAI Press: Greenwich, 1993; Vol. 14, pp 29–59.

(23) Blackman, M. J.; Stein, G. J.; Vandiver, P. B. The Standardization Hypothesis and Ceramic Mass Production: Technological, Compositional, and Metric Indexes of Craft Specialization at Tell Leilan, Syria. *Am. Anthropol.* **1993**, *58*, 60–80.

(24) Bishop, R. L.; Canouts, V.; De Atley, S.; Qöyawayma, A.; Aikins, C. W. The Formation of Ceramic Analytical Groups: Hopi Pottery Production and exchange, A. D. 1300–1600. *J. Field Archaeol.* **1988**, *15*, 317–337.

(25) Lothrop, S. K. *Pottery of Costa Rica and Nicaragua*, Memoir No. 8; Heye Foundation, Museum of the American Indian: New York, 1926.

(26) Lange, F. W. The Greater Nicoya Archaeological Subarea. In *The Archaeology of Lower Central America*; Lange, F. W., Ed.; University of New Mexico Press: Albuquerque, 1984; pp 165–194.

(27) Bishop, R. L.; Lange, F. W.; Lange, P. C. Ceramic Paste Compositional Patterns in Greater Nicoya Pottery. In *Costa Rican Art and Archaeology*; Lange, W., Ed.; The University of Colorado: Niwot, 1988; pp 11–44.

(28) Canouts, V.; Guerro, J. V. Vallejo and Jicote Ceramic Codes: The Case for Stylistic Analogy in the Late Polychrome Period. In *Costa Rican Art and Archaeology*; Lange, F. W., Ed.; The University of Colorado: Niwot, 1988; pp 213–260.

AR000199K