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Archeology and Dating by Hydration of Obsidian

This technique is a reliable, sensitive tool for relative and chronometric dating widely benefiting archeology.

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A relatively new technique for dating now available to archeologists has produced useful results when applied to a variety of archeological problems. The importance of dating controls in archeology makes the discovery and development of new dating techniques a matter of great interest. In the case of obsidian hydration dating, however, interest and enthusiasm is especially great due to its wide range of application to archeological analysis and to its low cost. Originally developed in 1958 by Friedman and Smith, the technique has been reported in three summary accounts (*1, 2*). Since 1959, and especially during the last 3 years, there has been rapid growth in the number of research programs aimed at further refinement of the technique, discovery of new applications, and application of the technique to the solution of substantive archeological problems.

Two obsidian-dating laboratories then existed (*3*); by the end of this year 11 laboratories will be operating, five of which have been established since 1964 (*4*). By 1960, 2000 dates had been produced; by 1968 we expect close to 9000 dates (Table 1). At the time of the early reports by Friedman and Smith, the dating technique was regarded as highly experimental and of doubtful reliability; today, after 3 years of massive intrasite sampling, many of the difficulties associated with use of the technique have been solved, and thus we know more of the nature of this new kind of data.

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History of Development

In 1958, Friedman and Smith began to collaborate on research designed to demonstrate that volcanic glass undergoes progressive alteration by diffusion of water into its interior (*5, 6*). Nonhydrated ("fresh") obsidian usually contains less than 0.3 percent water by weight and tends to adsorb water from the surrounding air or soil, which forms a film of molecular thickness. A process of diffusion then begins: when viewed with an ordinary light microscope, water drawn from the surface film appears to advance into the obsidian as a sharply demarcated front (*7*). The water-saturated zone thereby produced is referred to as the layer or rim of hydration. The layer contains approximately ten times more water than the nonhydrated interior of the obsidian does, and it has a higher index of refraction than the unaffected parts do. Because of this different index of refraction, the hydrated layer exhibits a distinct phase contrast under ordinary light: the boundary or interface between the hydrated and nonhydrated obsidian stands out sharply, and the depth of hydration can be measured under high magnification. Similarly, the greater water content of the hydrated layer increases the density of the layer and modifies its volume. This difference in volume between the hydrated and nonhydrated portions creates mechanical strains throughout the hydrated layer, strains which can be recognized under polarized light. The optical phenomenon observed under polarized light is called strain birefringence and appears as a measurable luminescent band.

Subsequent research by these men between 1958 and 1960 showed that this hydration process is continuous, and that the rate at which water diffuses into the stone's interior is uniform. Evans and Meggers (*8*) were called in by Friedman and Smith to supply specimens of ancient obsidian of known date. With these specimens Friedman and Smith were able to demonstrate that this process is continuous and has a uniform rate; thus was born the idea of using this hydration process as a rapid and inexpensive dating method for archeology.

The principle aim underlying early research in obsidian dating was to establish an absolute dating technique along the lines of radiocarbon dating, that is, a technique that would generate chronometric dates represented by a mean value and associated with a calculated standard deviation. Thus, the objective would be to determine that obsidian artifact A, for example, was manufactured in 4300 B.C. plus or minus 180 years. Clark (*9*) contributed significantly to the progress made during this early phase of research.

Several major difficulties discouraged immediate and wholesale acceptance of this new dating technique (*10*). It was discovered that the primary determinant of hydration rate is atmospheric or soil temperature, and, since this is variable around the globe, separate rates of hydration would have to be established for each microenvironment. Different kinds of obsidian proved to have different rates of hydration under identical temperature regimes; and archeological application of the technique uncovered wide-ranging patterns of artifact reuse among prehistoric communities, which can interfere with dating unless compensated for. During the last 3 years, however, reexamination of the utility of this dating technique has proved extremely fruitful, and solutions of the several difficulties have been found.

This second phase of research in obsidian dating was different in underlying strategy from the first. To avoid the problems connected with determining hydration rates of specific archeological areas, the method was no longer treated as a second cousin to radiocarbon dating, but as a highly precise tool for relative dating (*11, 12*). Relative dating programs, such as seriation of artifacts or site components, require large samples of dated materials, a requirement that radiocarbon dating cannot meet since the cost of dating is still so high (*13*). Obsidian dating, however, is cheap and fast. For the cost of one commercially processed radiocarbon date, the archeologist can obtain 80 or more obsidian dates; a sample size that can often yield a reliable profile of occupational intensity through time at a multicomponent site.

Instead of securing two or three obsidian dates from a single site, as is the pattern for radiocarbon dating, the archeologist now often obtains anywhere from 60 to 500 dates (*14*). Sampling from a single site was originally so massive for the purpose of seriating artifact types (*15*). However, many applications of such a large-scale dating sample soon began to emerge.

Table 1. Summary of obsidian dating projected to 1968 (based on available information). A total of 7543 artifacts and 307 sites have been dated. The proveniences of another 1400 artifacts have yet to be reported.

Geographical area	Artifacts dated (No.)	Sites sampled (No.)
New World		
Alaska	375	18
Oregon	414	6
California	1301	58
Northwestern Plains	500	50
Southwestern United States	53	16
Ohio	24	5
West Mexico	560	11
Valley of Mexico	3474	47
Guatemala	89	5
Ecuador	424	14
Africa		
Egypt	18	3
East Africa	29	10
Near East		
Near East	77	15
Asia		
Japan	65	35
New Zealand	140	14

Applications to Archeology

Relative-dating applications of this technique include study of the history of artifact style at a site. Since each artifact can be assigned a discrete hydration measurement, the investigator can serialize all specimens within an artifact class (such as projectile points) and can observe the behavior of stylistic traits, with time functioning as a fully controlled variable. Similarly, members of a typological set can be arrayed at measurable intervals along a temporal axis on the basis of their hydration measurement, and the investigator can determine the persistence of a type relative to other types of the same artifact class (*16*).

Artifact reuse has been identified as a major obstacle in the path of obsidian dating. It has also been a difficult factor to control for in archeological analysis, generally. Obsidian dating, however, provides several approaches to this problem: (i) the investigator can often detect two hydration rims of different thickness on the same specimen, suggesting a time of original manufacture and a later time of reuse; (ii) by measuring the hydration of a sample of associated tools, one can determine the percentages that either are of original manufacture or have been collected from the surface of the ground nearby and reused; (iii) by generating a three-dimensional scattergraph showing the distribution of artifact hydration measurements within a stratified site deposit, one can ascertain the presence or absence of a cultural pattern of artifact reuse by determining whether a period of time can be isolated during which there is marked intrusion of older artifacts into younger strata that correlates with a period of negligible artifact manufacture (*17*).

This latter approach to determination of reuse is connected with another very important application of the dating technique—the testing of site stratigraphy. Hitherto, we have had no economical way of determining the degree to which an archeological deposit conforms with the geologic principle of superposition; we all take conformity for granted, unless there is conspicuous evidence of systematic disturbance at the site. With this new technique one can observe the nature and extent of disturbance, and of artifacts' mixing, by plotting the distribution of hydration measurements on a three-dimensional scattergraph. Thus the archeologist can segregate geological stratigraphy from archeological or cultural stratigraphy. In application of this test, instances have been studied in which physical stratigraphy is conspicuously present while cultural stratigraphy obtains only in a statistically significant sense; that is, the disposition of the dated cultural materials indicates merely a tendency toward superposition, since large numbers of artifacts at all levels were very much out of place (*17*). This application of the technique is of great benefit in permitting the archeologist to evaluate the integrity of the association between a radiocarbon sample and the cultural matrix of the site that it is intended to date (*18*).

Another very useful application of this technique to relative dating is for determination of the relative intensity of occupation of the site through time. This one can do by graphing the frequency distribution, through time, of a large sample of artifacts postulated to be of primarily domestic utility; the resultant graph yields something analogous to a demographic curve for that site locality (*19*).

A related application has to do with the discovery of a commercial focus within a lithic industry. If a site became the locus of commercially motivated manufacture of artifacts, the graph of frequency distribution for that particular class of lithic artifacts exhibits a curve that does not conform with those for other classes of artifacts; it shows a conspicuous rise in the production of artifacts of that class along a specific segment of the curve. Isolation of periods of commercially motivated production of artifacts at a site allows the archeologist to sketch, in broad outline, the temporal and geographic parameters of a trading network.

Perhaps the most fundamental contribution of the technique is its use by archeologists to associate artifacts with each other for the purpose of forming artifact complexes in the absence of reliable stratigraphy. For the first time, we have a perfectly unbiased procedure for segregating surface materials, and materials from poorly stratified or unstratified sites, into analytically useful units of association. Segregation is accomplished by establishing arbitrary micron ranges and treating all artifacts having hydration values falling within the established range as in some sense associated. Artifacts having hydration values falling outside the range then belong to other similarly constituted units of association. For artifact samples that are very large, an added advantage is achieved by constituting dead spaces between micron range units. All artifacts having hydration values falling within these dead spaces are excluded from analysis; this has the effect of artificially creating what can be figuratively described as sterile layers between deposits of cultural refuse, so that the absence of all contamination is ensured.

A final relative-dating application is for identification of horizontal stratigraphy at a site; identification is especially useful for surface sites or sites having very shallow deposits. A systematic program of surface sampling, although revealing mixture, may also reveal meaningful variation in the relative frequency of hydration values over space in such a way as to imply horizontal stratigraphy.

Dating Controls

All these applications pertain to single-site analysis or to analysis of multiple sites within a homogeneous climatic zone. This is because relative-dating applications of the technique are based on the assumption that the rate of hydration affecting all collections is uniform; and only at a single site or within a homogeneous climatic zone is that assumption warranted. Very often these zones of homogeneous climate are so extensive that studies on a regional scale can be undertaken; the investigator is thus permitted to extend many of the previously mentioned applications to a relatively extensive culture area. I am currently undertaking such studies for 47 sites distributed throughout the Valley of Mexico, which is just such a climatically homogeneous zone (*20*). A sample of more than 3500 artifacts is to be dated in the process.

So that obsidian dating may yield chronometric dates, a rate of hydration must be established that accurately reflects the temperatures to which the artifacts have been exposed since their original manufacture. Rates may be established in either of two ways: the investigator may correlate hydration measurements with points along an independent chronometric scale such as radiocarbon dating or dendrochronology; or he can calculate the effective temperature of the locality in which the obsidian was found, and use the hydration equation of Friedman, Smith and Long ($X^2 = Kt$, where X is the depth of penetration of water in microns, K is the effective temperature constant, and t is the time in years) (*6*).

Friedman and Smith originally established seven different rates of hydration (*2*): one Arctic, one Subarctic, two temperate, one for coastal Ecuador, and two for Egypt, reflecting the presence of two kinds of obsidian there (rhyolitic and trachytic). These rates have been subject to reexamination, and new rates have been added. Clark established a rate for central California, based on the association of obsidian artifacts with five radiocarbon-dated burial sites (*21*). Evans' test of the Ecuadorian rate established by Friedman and Smith showed that it worked quite well (*22*). Koch (*23*) identified permafrost as an important variable not originally considered in Friedman and Smith's Arctic hydration rate; he suggested a tentative new rate. Independently, Friedman, Smith, and Long (*6*) have since revised the original rates for the Arctic and Subarctic, but this revision does not yet resolve the role of permafrost as a variable. Katsui and Kondo (*24*) have established a rate for Hokkaido using obsidian from six nonceramic to post-Jomon sites that have been radiocarbon dated. Meighan (*18*) is currently establishing a rate for West Mexico based on many obsidian samples associated with radiocarbon-dated material. An effort will be made to establish a rate for the Sierra Nevada Piedmont, central California, on the basis of 12 radiocarbon samples currently being processed from two obsidian-chipping stations in that area (*11*); and I am currently evaluating the accuracy of one of Friedman and Smith's temperate rates for materials in the Valley of Mexico.

Tests of uniformity, accuracy, and reliability have been developed and applied to this dating technique; both field and laboratory data have been used (*25*). Tests of uniformity are concerned with determining whether or not the forces that produce hydration act uniformly on identical materials under identical conditions. Two field tests of uniformity have been made, one by Clark on obsidian lots associated with burials (*21*) and one by me on restored knife segments (*12*). Both results support the assumption of uniform hydration effects on similar materials under similar conditions. Studies by Friedman, Smith, and Long of artificially induced hydration also support this assumption (*6*).

Tests of reliability are really tests of reproducibility of measurement. It is measurement error that contributes practically all the variation between uniform samples. Refinements in the preparation of thin sections and modifications in microscopy techniques, especially the adoption of the image-splitting eyepiece (*26*), have caused a significant reduction in the degree of error associated with the measuring process. Reliability tests performed recently at the Pennsylvania State University laboratory indicate that our present measurements have a standard deviation of 0.07 micron.

A factor contributing to the early lack of interest in obsidian dating was the belief that it only worked on obsidian and was therefore of only regional interest. Archeologists have since begun to notice that many of the most critical areas of prehistoric research feature heavy utilization of obsidian: the Arctic, western North America, Mexico, Central and South America, East Africa, Egypt, the Near East, the classic world of the Mediterranean, and parts of Japan, to name only a few. Moreover, we have discovered that materials other than obsidian do hydrate; one such, now being analyzed by Bebrich (*27*), is Los Angeles County fused shale, a material that is similar in fracturing properties to obsidian and that was used for the manufacture of tools by the prehistoric residents of Southern California. Although the study is incomplete, the shale appears to hydrate faster than rhyolitic obsidian. I predict that materials such as artificial glass, furnace slag, and some kinds of ceramic glazes will prove to undergo hydration and to be susceptible to dating by this technique.

Thus, obsidian-hydration dating is emerging as a highly versatile tool for general archeological analysis, as well as a proven instrument of relative and chronometric dating. The few years that have elapsed since the discovery of this technique have witnessed important developments in evaluation and application that have secured for it a permanent place among the dating programs now available to archeology.

References and Notes

1. R. L. Smith and I. Friedman, *Actas Congr. Int. Americanistas 33rd, San Jose, Costa Rica* **2**, (1958); I. Friedman and R. L. Smith, paper read at annual meeting, American Anthropological Association, Mexico City (1959).
2. I. Friedman and R. L. Smith, *Amer. Antiquity* **25**, 476 (1960).

3. The laboratory directed by I. Friedman and R. L. Smith at the U.S. Geological Survey, Washington, D.C., and the laboratory at Stanford University, directed by D. Clark.
4. They are, in order of establishment: U.S. Geological Survey, Denver (I. Friedman); Stanford University (B. Gerow); Smithsonian Institute-Anthropology (C. Evans); University of Auckland, New Zealand (R. C. Green); Brown University (D. D. Anderson); University of Hokkaido (Y. Katsui and Y. Kondo); University of California, Los Angeles (C. W. Meighan); University of California, Davis (M. Baumhoff); Pennsylvania State University (J. W. Michels); University of Oregon (L. Johnson); University of Manitoba (W. J. Mayer-Oakes).
5. I. Friedman and R. L. Smith, *Geochim. Cosmochim. Acta* **15**, 218 (1958).
6. I. Friedman, R. L. Smith, W. D. Long, *Bull. Geol. Soc. Amer.* **77**, 323 (1966). Also an important background paper: C. S. Ross and R. L. Smith, *Amer. Minerol.* **40**, 1071 (1955).
7. An electron photomicrograph image of the hydrated region reveals a sector exhibiting parallel microfractures all running perpendicular to the exterior surface of the stone and terminating at approximately the same point. The sharply demarcated front seen through an ordinary light microscope is an optical smear of the interior ends of the microfracture lines. D. Gibbon and J. W. Michels, *Proc. Electron Microscop. Soc. Amer.*, in press.
8. Archeologists with the Smithsonian Institution.
9. D. Clark, paper read at annual meeting, American Anthropological Association, Mexico City (1959); *Curr. Anthropol.* **2**, 111 (1961).
10. C. Evans and B. J. Meggers, *Amer. Antiquity* **25**, 523 (1960).
11. J. W. Michels, *Annu. Rep. Univ. Calif., Los Angeles, Archeol. Surv.* **7**, 377 (1965).
12. J. W. Michels, thesis, University of California, Los Angeles (1965).
13. Commerical radiocarbon-dating laboratories charge approximately $160 per date.
14. I am currently dating specimen lots with that size range from 30 sites of the Valley of Mexico. Also see, for example, C. Evans, in *Reports of the Norwegian Archeological Expedition to Easter Island and the East Pacific* (School of American Research and KonTiki Museum, Phoenix, Arizona, 1965), pp. 469–95; K. Dixon, *Amer. Antiquity* **31**, 640 (1966).
15. I dated 500 artifacts from the Mammoth Junction Site (MNO 382), California, for this purpose in 1964.
16. J. W. Michels, paper read at annual meeting, American Anthropological Association, Denver, Colorado (1965).
17. J. W. Michels, paper read at annual meeting, Society for American Archeology, Reno, Nevada (1966).
18. C. W. Meighan, "Obsidian Dates Correlated with Radiocarbon Dates from the Morret Site, Colima, Mexico," unpublished.
19. J. W. Michels, "The Occupational History of the Maquixco Site, Valley of Mexico," paper read at the Mesa Redonda 11th, Mexico City (1966).
20. J. W. Michels, "The Structure and Function of the Prehispanic Obsidian Industry of the Basin of Mexico," National Science Foundation grant No. GS-1256.
21. D. L. Clark, *Ann. Rep. Archeol. Surv., Univ. Calif., Los Angeles* **6**, 143 (1964).
22. B. J. Meggers, C. Evans, E. Estrada, in *Smithsonian Contributions to Anthropology* (Smithsonian Institution, Washington, D.C., 1965), vol. 1, pp. 147–156.
23. W. Koch, "Report on Brown University's Obsidian Hydration Dating Laboratory," unpublished.
24. Y. Katsui and Y. Kondo, *Jap. J. Geol. Geography* **36**, 45 (1965).
25. A manual of obsidian hydration dating is currently being prepared at Pennsylvania State University by J. W. Michels and C. Bebrich and will report in detail all available evidence regarding questions of uniformity, accuracy, and reliability.
26. J. Dyson, *J. Opt. Soc. Amer.* **50**, 754 (1960).
27. C. A. Bebrich is a research assistant in the Pennsylvania State University obsidian dating laboratory.

Optical Methods for Studying Hertzian Resonances

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During my first year of studies at the Ecole Normale Supérieure in Paris, our teacher, Eugène Bloch, introduced us to quantum physics, which at that time was little taught in France. Like he, I was of Alsatian extraction and knew German. He strongly advised me to read Sommerfeld's admirable book *Atombau und Spektrallinien* (*1*). In the course of this reading, I became particularly interested in the application of the principle of conservation of momentum during interactions between electromagnetic radiation and atoms, an application which had led A. Rubinowicz (*2*) to the interpretation of the selection rules for the azimuthal quantum number and polarization in the Zeeman effect. In the hypothesis of light quanta, this principle attributed to the photons a momentum $+\hbar$ or $-\hbar$ according to whether the light was polarized circularly to the right (σ^+) or to the left (σ^-), natural light being a mixture of the two kinds of photons.

In 1931, W. Hanle and R. Bär (*3*) independently discovered an interesting characteristic of Raman spectra. The study of the polarization of Raman lines at right angles to the incident beam made it possible to classify the Raman lines of a molecule into two categories: "depolarized" lines with a depolarization factor of 6/7 and "polarized" lines, whose polarization was generally appreciable. Placzek's theory had attributed the former to periodic molecular motions which modify the symmetry elements the molecule possesses at rest, among which are included rotational Raman lines, and the latter to totally symmetric vibrations which maintain the symmetry elements of the molecule at rest.

Hanle and Bär illuminated the medium with circularly polarized incident light and observed that, under these conditions, the Raman lines scattered longitudinally had the same circular polarization as the incident light in the case of totally symmetric vibrations, but that the direction of circular polarization was reversed for lines not totally symmetrical. In a note (*4*), I pointed out that for rotational lines this curious result was an immediate consequence of the principle of conservation of momentum applied to light scattering.

At about the same time, Jean Cabannes (*5*) explained the Hanle and Bär result by the classical polarizability theory, but these publications had been preceded by an article of Raman and Bhagavantam (*6*) who saw proof of the existence of photon spin in the experimental results cited.

At the time, another experiment seemed to me appropriate for demonstrating the possible existence of a transverse component of the momentum of photons: the study of linearly polarized light originating from a rotating atomic oscillator and viewed edge on. This case arises for the σ components of the transverse Zeeman

The author is Professor of Physics at the Ecole Normale Supérieure, Paris, France. This article is a translation of the lecture he delivered in Stockholm, Sweden, 12 December 1966, when he received the Nobel Prize in physics. It is published here with the permission of the Nobel Foundation and will also be included in the complete volume of *Les Prix Nobel en 1966* as well as in the series Nobel Lectures (in English), published by the Elsevier Publishing Company, Amsterdam and New York.