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Obsidian Dating and East African Archeology

Joseph W. Michels, Ignatius S. T. Tsong, Charles M. Nelson

Summary. New experimental procedures have made it possible to establish specific hydration rates for the numerous compositional types of obsidian to be found at archeological sites in Kenya. Two rates are applied to artifacts from the Prospect Farm site, revealing a history of occupation extending back 120,000 years.

East Africa has been regarded for some time as an ideal archeological region for obsidian hydration dating (*1*). Obsidian artifacts are common in prehistoric sites of the area, and the dating technique can potentially provide ages for artifacts 1/2 million years old, beginning with sites as recent as 150 years. Although the technique has been known for 20 years (*2*) virtually no attempt was made until recently to apply hydration dating to this region. In contrast more than 10,000 obsidian dates now contribute to regional chronologies for western North America and Central America.

At the Pennsylvania State University Obsidian Dating Laboratory, a broad program of basic research on obsidian hydration was under way, and it seemed appropriate to illustrate recent developments in the dating technique by a practical application to East Africa. Obsidian artifacts representing site collections from throughout Kenya, but principally the Naivasha-Nakuru basin region (Fig. 1), were made available for study.

The Obsidian Dating Technique

The dating of obsidian artifacts is based on the fact that when a fresh surface of obsidian is exposed to the atmosphere, the diffusion of ambient water causes a hydrated layer to form just below the surface. The thickness of this hydrated layer, which varies from less than 1 micrometer to more than 50, depending on the time of exposure, can be measured by optical microscopy.

Because the hydration of obsidian is a diffusion process, it should obey the equation of Friedman and Smith (*2*)

$$x^2 = kt \qquad (1)$$

where x is the thickness of the hydrated layer, k the hydration rate, and t the time. The hydration rate is temperature dependent and follows the Arrhenius equation

$$k = Ae^{-E/RT} \qquad (2)$$

where A is a constant, E the activation energy, R the universal gas constant, and T the temperature. Combining Eqs. 1 and 2 gives

$$x^2 = Ate^{-E/RT} \qquad (3)$$

Accelerated Hydration Experiments

Various accelerated hydration experiments have been undertaken in connection with the depth-profiling of hydrogen by ion-beam techniques (*3*). Of greater practical importance to archeologists, however, are experiments that produce sufficient hydration so that observation and measurement by optical microscopy are possible.

In 1966 Friedman *et al.* published the results of an experimental hydration of obsidian from the Valles Mountains of New Mexico at an elevated temperature of 100°C (*4*). Freshly exposed obsidian surfaces underwent induced hydration at varying lengths of time up to 4 years. The results supported Eq. 1. After a

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decade, during which that equation came under attack (5), Friedman and Long (6) published the results of a much more ambitious and comprehensive program of laboratory-induced hydration, involving 12 geologically identifiable obsidian sources. Additional work in this area was undertaken by Ericson (7) on California obsidian.

We have undertaken numerous induced hydration experiments during the past year and at last count had completed experiments on 22 geologically identifiable obsidian sources from four continents. Although many experiments are still in progress, those for which analyses are complete offer support for several conclusions. First, the results are compatible with Eq. 1. Second, Eq. 2, which related hydration rate to temperature, is applicable to obsidian experimentally hydrated at temperatures as high as 250°C and pressures up to 580 pounds per square inch, confirming the findings of Friedman and Long (6). Third, chemical attack (etching) of the surface of obsidian does take place when temperature and water pressure are elevated, with a consequent threat to the physical integrity of the hydrated layer. However, it has been found that the etching effect does not result in congruent dissolution of surface layers but only affects those surface regions with imperfections that give rise to accelerated etching. The parameters that appear to be satisfactory in preventing total surface dissolution are discussed below.

A successful experimental procedure for inducing hydration that can be measured by optical microscopy allows us to determine both a hydration rate (at a fixed temperature) and an activation energy value for any geologically identifiable source. To arrive at an archeologically relevant hydration rate one need only determine the effective hydration temperature at the site and solve for the rate by means of the Arrhenius equation.

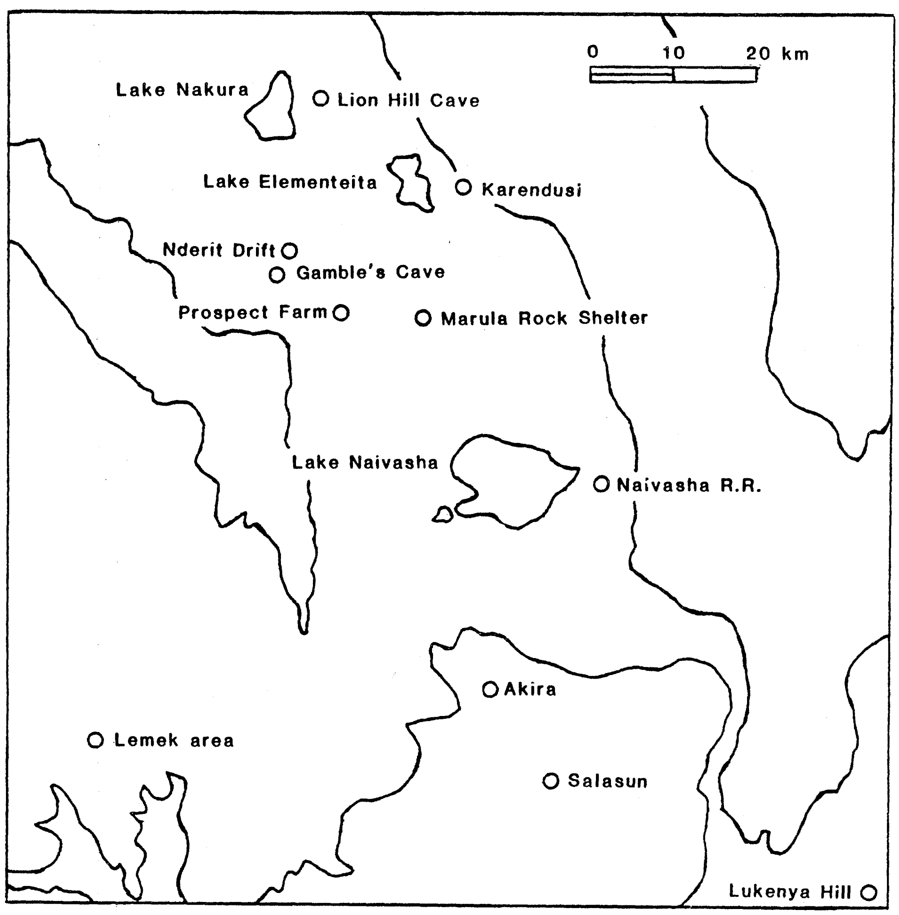
Composition-specific hydration rates. Two samples, representing the two main compositional groups (A and B) from the study area, were used in the experiment (Table 1). The specimens were fractured by percussion and nine small flakes with fresh surfaces were selected from each. The 18 flakes underwent induced hydration in a 1-liter, thermoregulated reaction vessel containing 500 milliliters of deionized water (Table 2). After thin-sectioning, hydration measurements were taken under transmitted, polarized light (between crossed Nicol prisms) by means of an optical microscope equipped with an oil immersion objective (magnification ×100) and a Vicker's image-splitting eyepiece.

A hydration rate plot for Kenya A and B obsidians (Fig. 2) was obtained from hydration measurements on samples 1 through 5 in Table 2. The Kenya A obsidian has a rate of 6.16 μm^2 per day at 200°C, and a correlation coefficient (r) of .99; the Kenya B rate is 14.80 μm^2 per day at 200°C (r = .99). Results of hydration measurements on samples 4 and 6, 7, 8, and 9 (Table 2) are plotted logarithmically in Fig. 3. Linear regression analysis yielded an activation energy of 20,672 calories per mole (86,535 joules per mole) for Kenya A (r = .99) and 19,239 cal/mole (80,534 J/mole) for Kenya B (r = 0.99).

Effective hydration temperature. To determine the effective hydration temperature it is necessary to take into consideration fluctuations of temperature around the annual mean because the rate of change of the chemical reactions increases as a function of temperature. Lee (8) has experimentally derived an equation that uses mean air temperature data (monthly mean temperatures averaged over a period of years) to determine the effective temperature (9)

$$T_a = -1.2316 + 1.0645 T_e - 0.1607 R_T \quad (4)$$

where T_a is the mean annual air temperature, R_T is the temperature range of T_a, and T_e is the effective temperature. Using data from the Nakuru Meteorological Station, for (average) monthly mean air temperature (10), we find that T_a = 18.2°C and R_T = 2.4°C (August mean subtracted from March mean); thus



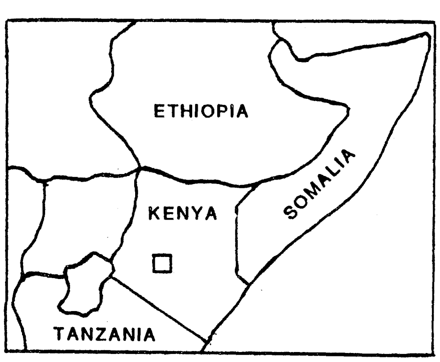


Fig. 1. Archeological sites and obsidian sources (○) in the Naivasha-Nakuru basin region of Kenya; the basin is located in the box in the small map.

T_e = [(18.2 + 1.2316) + (0.1607)(2.4)]/ 1.0645 for an effective hydration temperature of 18.62°C (291.78 K).

Hydration rates. To determine the hydration rates of Kenya A and B obsidians at archeological sites in the Naivasha-Nakuru basin region we begin with the expression derived from the Arrhenius equation

$$k' = k \exp\left[\frac{E}{R}\left(\frac{1}{T} - \frac{1}{T'}\right)\right] \quad (5)$$

where k' is the hydration rate at T' (of the unknown), k the hydration rate at T determined by induced hydration (6.16 μm^2 per day for Kenya A and 14.80 μm^2 per day for Kenya B), E the activation energy determined by induced hydration (86,535 J/mole for Kenya A and 80,534 J/mole for Kenya B), R = 8.317 J/mole per degrees Celsius (gas constant), T = 473.16 K (200°C) (induced hydration temperature), and T' = 291.78 K (effective hydration temperature of Naivasha-Nakuru basin). Thus for Kenya A obsidian, k' = 0.0000071 μm^2 per day or 2.60 μm^2 per 1000 years; for Kenya B obsidian, k' = 0.0000442 μm^2 per day or 16.14 μm^2 per 1000 years.

Kenya Obsidian

Bulk element compositional analyses were performed on 138 artifacts and 14 quarry samples by atomic absorption spectroscopy. The artifacts were selected from 15 different archeological sites located throughout the study area. Gross differences in chemical composition justified the establishment of a third major compositional grouping (Kenya C) in addition to A and B (Table 1).

The hydration dating of Kenya obsidian requires the proper compositional identification of each artifact so that the appropriate hydration (source) rate can be applied. This can be achieved most reliably by means of instrumental analysis, such as x-ray fluorescence, atomic absorption spectroscopy, and neutron activation analysis. However, as we worked with the analyzed samples it became clear that differences in translucence and coloring made it possible to correctly identify a specimen's compositional group affinity by visual inspection.

The capacity to resist chemical attack and etching appears to vary considerably between Kenya A and B obsidians. Although Kenya A obsidian hydrates slowly (2.60 μm^2 per 1000 years), it is highly susceptible to surface pitting and etching under the conditions of archeological interment characteristic of Kenya. Examination of what appear, in the hand, to be unweathered surfaces reveals noticeable etching in scanning electron micrographs. Slightly weathered obsidian surfaces are shown by these micrographs to be extensively pitted. Apparently, the hydration rim can undergo partial to total spalling beginning after about 50,000 years, and the fresh hydrated zone that then forms could be confused with the original, giving a spuriously recent date. Careful examination of the entire edge of the microscope thin section often reveals a remnant of the original hydration rim; sometimes such remnants are only 50 to 60 μm long. Although our studies are still preliminary, it appears that Kenya B obsidian resists surface etching and pitting far better than obisidan of Kenya A. This came as a surprise since B obsidian hydrates at an unusually high rate (16.14 μm^2 per 1000 years). Analysis of Kenya C obsidian is not complete.

Table 1. Chemical composition of two obsidian samples that were used in the induced hydration experiments and that represent the two major compositional groups found at the study area.

Compound	Composition (percent by weight)	
	12226 (group A)	13420 (group B)
SiO_2	72.7	75.6
Al_2O_3	7.85	12.17
Na_2O	6.46	4.53
K_2O	4.35	5.00
Fe_2O_3*	8.09	2.06
CaO	0.31	0.46
MgO	0.04	0.07
TiO	0.16	0.11

*Total Fe.

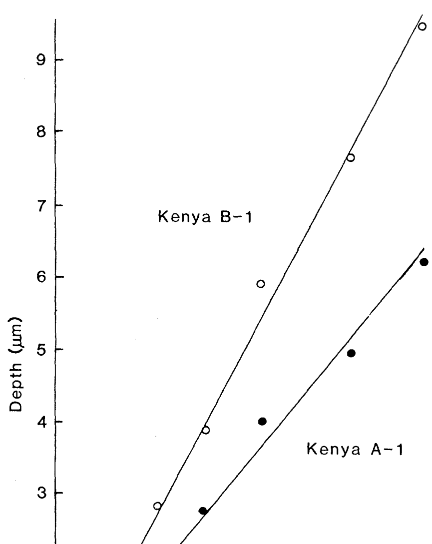


Fig. 2. Induced hydration rates at 200°C of Kenya obsidians A and B.

The Prospect Farm site. The Prospect Farm site (Fig. 1) is located about 35 kilometers south of the Nakuru Meteorological Station and within the same ecozone (1829 to 2154 meters above sea level). The site was chosen to illustrate the possibilities of obsidian dating in East Africa because (i) its proximity to the weather station ensured that the calculated effective hydration temperature would be applicable, (ii) its history of occupation extends from the Middle Stone Age to the Pastoral Neolithic, and (iii) its samples of both Kenya A and B obsidians would make it possible to assess the degree of correspondence between the two hydration rates.

Discussion of Results

The Prospect Farm site is located on Mount Eburru, a transverse structure in the Gregory Rift, which is mantled with volcanic deposits, including air-fall pyroclastics, ignimbrites, and flows of lava and obsidian. Prospect Farm is situated on the northern flank of Mount Eburru, where more than 30 m of pyroclastic sediments and derived colluvium, known as the Prospect Farm Formation (*11, 12*), are interstratified with numerous weathering zones and archeological horizons. Radiocarbon dates high on the flank of Eburru indicate that all but 30 centimeters of this succession had accumulated by 10,000 years ago (*12, 13*). At lower elevations, the Prospect Farm Formation interdigitates with alluvial beds of the Nakuru River and lacustrine deposits of ancient Lake Nakuru. All but the upper 50 cm of alluvium derived from the Prospect Farm Formation accumulated by at least 30,000 years ago (*11, 14, 15*), suggesting an early date for the lower archeological horizons at the Prospect Farm site.

Excavations at the site have revealed four main episodes of occupation (*11, 16, 17*): the Middle Stone Age, the Second Intermediate, the Eburran Industry, and the Pastoral Neolithic.

Middle Stone Age. There is a series of Middle Stone Age horizons containing four phases of the Prospect Industry (*12*). Efforts to date obsidian from phase 1 were not successful. Artifacts that appeared to be moderately weathered were consistently of group A, which hydrates slowly but is highly susceptible to chemical attack. The original surfaces of these specimens have been removed by etching and spalling.

All of the specimens from phase 2 have heavily spalled surfaces beneath which remnant hydration rims yielded dates ranging from 14,700 to 24,500 years ago. On some specimens, small, unspalled remnants remain and constitute less than 1 percent of the surface. These remnants, which themselves appear eroded and incomplete, yield dates ranging from 81,800 to 88,400 years ago.

Phase 3 obsidian dating was more successful. The hydration dates and stratigraphic profile suggest three separate periods of occupation. First, the interface of strata 9 and 10 yielded a date of nearly 120,000 years ago (Table 3). Second, stratum 9, which is capped by a well-developed fossil soil, has produced dates ranging from 106,300 to 108,600 years ago (Table 3). These dates are in agreement with other early age determinations on Middle Stone Age horizons in northeastern Africa (*18*). All the artifacts are heavily spalled. The remnants of the hydration rim below the spalled surfaces produce dates ranging from 14,900 to 18,300 years ago. However, these specimens preserve larger unspalled areas which appear less extensively weathered and, for this reason, these dates are thought to be more accurate than those for phase 2.

The third period in phase 3 is represented by 35 cm of colluvium from the top of stratum 8 to the interface of strata 8 and 9. These occurrences yielded obsidian dates ranging from 46,500 to 53,100 years ago (Table 3).

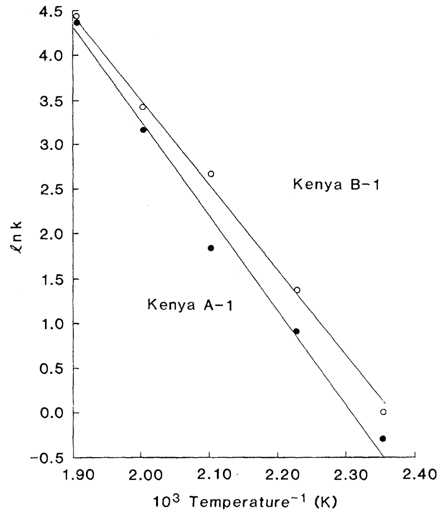


Fig. 3. Arrhenius plots for Kenya obsidians A and B.

Phase 4 of the Prospect Industry was encountered in strata 6 and 7 and produced hydration dates of 46,700 to 53,600 years, a range virtually identical with that obtained for the upper portion of phase 3 (Table 3). Archeologically, phase 4 represents the transition between local Middle Stone Age and Second Intermediate technologies. At Prospect Farm, this is marked by the disappearance of points and refined Levallois techniques and the appearance of small discoidal knives and scrapers. This transition is already under way late in phase 3, where points and refined Levallois cores make up only 10 and 12 percent, respectively, of shaped tools and discoidal knives and scrapers make up 8 percent. At the base of phase 4, points make up 7 percent, disks 41 percent, and sophisticated Levallois techniques are absent. By the end of phase 4, points are virtually absent and thumbnail scrapers, a hallmark of the Later Stone Age, have been introduced (*12*). Thus we can fix the beginning of the Second Intermediate in East Africa between 45,000 and 50,000 years ago.

The obsidian dates from the base of stratum 5 to the upper portion of stratum 8 reflect complete hydration rims on artifacts of both Kenya A and B obsidians, and thus invite a comparison of the results of rapid hydration in corrosion-resistant obsidians with slow hydration in obsidians susceptible to corrosion. The slowly hydrating glass yields dates ranging from 47,800 to 53,100 years ago, and the rapidly hydrating glass yields dates ranging from 45,700 to 53,600 years ago (Table 3). These results are remarkably consistent, given the time depth and different chemical characteristics of the two groups of glasses, and provide excellent corroboration of the stability of hydration rates in volcanic glasses and of the diffusion model used to calculate these rates.

Second Intermediate or early Later Stone Age. Superposed 1.5 m above phase 4 of the Prospect Industry, in stratum 2, is an early Later Stone Age or Second Intermediate Industry represented in sparse occurrences which contain few diagnostic tools (*12*). Stratum 2 consists of three superimposed B soil horizons which probably represent successive periods of soil development. Hydration dates from these units range from 21,800 to 32,500 years ago (Table 3).

The Eburran Industry. Occurrences of Second Intermediate Industry in stratum 2 are overlaid by 8 cm of topsoil containing a smattering of Later Stone Age artifacts, including crescents, curved-backed flakes, and burins (*12*). The artifacts yielded hydration dates ranging from 14,100 to 14,500 years ago (Table 3). At another part of the site, there is a rich occurrence of the Eburran Industry (*12, 13, 16*), which was found in 90 cm of colluvium that overlie the Prospect Farm Industry (*12*). It is associated with ^{14}C date of 10,560 ± 1650 years ago (sample GX-224) on scattered charcoal from the base of the Eburran horizon. Elsewhere, the Eburran Industry is associated with ^{14}C dates ranging from 7000 to 12,000 years ago (*16*). Hydration dates from the Eburran Industry at Prospect Farm range from 9612 to 10,845 years ago and are in good agreement with the ^{14}C chronology.

The Pastoral Neolithic. Anthony (*13*) tested a Pastoral Neolithic occurrence in

Table 2. Measurements of induced hydration (± standard deviation) from specimens representative of compositional types A and B, Kenya.

Sample	Temperature (°C)	Pressure (pounds per square inch)	Duration (days)	Hydration depth (μm)
		Kenya A		
12226-1	200	240	0.5	2.01 ± 0.07
12226-2	200	240	1	2.74 ± 0.07
12226-3	200	250	2	4.07 ± 0.10
12226-4	200	250	4	4.95 ± 0.12
12226-5	200	250	6	6.19 ± 0.34
12226-6	250	580	4	18.43 ± 0.38
12226-7	225	400	4	10.20 ± 0.25
12226-8	175	160	4	3.04 ± 0.19
12226-9	150	80	4	1.75 ± 0.06
		Kenya B		
13420-1	200	240	0.5	2.84 ± 0.14
13420-2	200	240	1	3.88 ± 0.11
13420-3	200	250	2	5.93 ± 0.18
13420-4	200	250	4	7.68 ± 0.33
13420-5	200	250	6	9.43 ± 0.14
13420-6	250	580	4	18.16 ± 0.11
13420-7	225	400	4	11.29 ± 0.18
13420-8	175	160	4	3.87 ± 0.14
13420-9	150	80	4	2.03 ± 0.06

colluvium overlying the Prospect Farm Formation, obtaining a ^{14}C date on charcoal of 2690 ± 80 years ago (sample UCLA-1234). Subsequently, Cohen (*17*) enlarged her excavation and obtained a ^{14}C age on charcoal from the main horizon at the site of 2910 ± 110 years old (sample N-651). Hydration analysis of 26 specimens suggests that these ^{14}C dates represent two separate occupations of the site. Two specimens yielded dates of around 2570 ± 100 years ago, and the other 24 samples gave dates ranging from 2815 to 3279 years ago, average 3042 years. These dates are in good agreement with the ^{14}C chronology.

We should note that the hydration rates used in dating the Prospect Farm succession were calculated without reference to the local or regional ^{14}C chronology. The close agreement between the results of the hydration measurements, the ^{14}C dates, and the stratigraphic succession at the site suggest that obsidian hydration dating will have many applications in northeastern Africa.

Applications in East Africa

Our results illustrate advances in obsidian dating and its potential application to periods of great antiquity in northeastern Africa. Obsidian is abundant along the Gregory Rift in Kenya and Ethiopia, a zone 100 km wide and 1400 km long; and archeological evidence indicates that it was used commonly to manufacture stone tools from Acheulean times (*19*). It was traded to adjacent regions as early as the Middle Stone Age (*20*), although, in Kenya, it was not until the Pastoral Neolithic period that trade became intensive and widespread (*21*). In this regional context, hydration dating has important potential applications in four areas.

1) It is difficult to obtain absolute dates of archeological events in East Africa between 20,000 and 500,000 years ago because of the scarcity of adequate samples. Obsidian hydration dating provides a means of scaling and correlating large numbers of sites throughout this period. The pace and character of technological change, and the ability to make regional correlations throughout Africa and the Mediterranean basin during this period, are vital to our understanding of the development of cultural behavior among humans. Hydration dating provides a basis for building regional components of that framework on a north-south axis along which it is difficult to achieve other forms of correlation.

2) Because well-associated samples of wood charcoal are uncommon in sediments more recent than 20,000 years old, bone must be used for ^{14}C dating. Experience has shown that bone collagen does not often survive in easily extracted forms for more than 2500 years, making bone apatite the most widespread material amenable to ^{14}C dating at archeological sites 2500 to 20,000 years old. But apatite is susceptible to contamination and, in Kenya, characteristically yields

Table 3. Obsidian dates and hydration measurements (± standard deviations) from the Prospect Farm site, Kenya.

Stratum	Specimen	Group	Date* (years)	Hydration measurement (μm)
		Phase 3, Prospect Industry		
9	13311	A	119,646 ± 1668	17.64 ± 0.12
9	13310	A	106,297 ± 3163	16.62 ± 0.25
9	13309	A	108,630 ± 2917	16.81 ± 0.22
9	13308	A	107,201 ± 3430	16.70 ± 0.26
8 and 9	13307	A	51,308 ± 4260	11.55 ± 0.26
8	13306	A	47,816 ± 1295	11.15 ± 0.15
8	13333	A	46,538 ± 1707	11.00 ± 0.20
8	13305	A	48,160 ± 1649	11.19 ± 0.19
8	13304	A	53,100 ± 4145	11.75 ± 0.45
8	13302	A	51,843 ± 4096	11.61 ± 0.45
8	13301	B	48,887 ± 769	28.09 ± 0.22
8	13300	A	50,777 ± 3322	11.49 ± 0.37
		Phase 4, Prospect Industry		
7	13299	A	47,816 ± 2256	11.15 ± 0.26
7	13298	B	45,670 ± 236	27.15 ± 0.07
6 and 7	13297	B	49,621 ± 281	28.30 ± 0.08
6	13296	B	52,106 ± 252	29.00 ± 0.07
6	13295	B	53,553 ± 255	29.40 ± 0.07
5-6 junction	13294	B	49,586 ± 210	28.29 ± 0.06
5	13293	B	52,936 ± 836	29.23 ± 0.23
		Second Intermediate (early Later Stone Age)		
2	13292	A	30,808 ± 762	8.95 ± 0.11
2	13291	A	32,483 ± 568	9.19 ± 0.08
2	13290	B	22,155 ± 329	18.91 ± 0.14
2	13289	B	24,635 ± 696	19.94 ± 0.28
2	13288	B	21,805 ± 373	18.76 ± 0.16
		Later Stone Age (unidentified industry)		
1	13287	B	14,145 ± 874	15.11 ± 0.46
1	13286	A	14,452 ± 1350	6.13 ± 0.28
		Eburran Industry		
1	13360	B	10,845 ± 114	13.23 ± 0.07
1	13363	A	9,905 ± 357	5.07 ± 0.09
2	13364	A	10,090 ± 673	5.12 ± 0.17
2	13365	A	9,905 ± 535	5.07 ± 0.14
2	13366	A	9,905 ± 535	5.07 ± 0.14
2	13367	B	10,460 ± 173	12.99 ± 0.11
2	13368	A	10,277 ± 445	5.17 ± 0.11
2	13376	A	9,612 ± 470	5.00 ± 0.12
2	13377	A	9,979 ± 622	5.09 ± 0.16
2-3 junction	13380	B	10,522 ± 224	13.03 ± 0.14
		Pastoral Neolithic, lower horizon		
	13334	B	2,840 ± 161	6.77 ± 0.19
	13335	A	3,124 ± 245	2.85 ± 0.11
	13336	A	3,102 ± 177	2.84 ± 0.08
	13337	A	3,279 ± 205	2.92 ± 0.09
	13338	A	2,930 ± 64	2.76 ± 0.03
	13339	A	2,994 ± 86	2.79 ± 0.04
	13340	A	2,951 ± 107	2.77 ± 0.05
	13358	A	3,257 ± 250	2.91 ± 0.11
	13341	A	3,059 ± 154	2.82 ± 0.07
	13342	A	3,080 ± 177	2.83 ± 0.08
	13359	A	3,168 ± 133	2.87 ± 0.06
	13343	A	3,015 ± 175	2.80 ± 0.08
	13344	A	3,168 ± 293	2.87 ± 0.13
	13345	B	2,815 ± 204	6.74 ± 0.24
	13346	A	3,146 ± 133	2.86 ± 0.06
		Pastoral Neolithic, upper horizon		
	13354	B	2,578 ± 80	6.45 ± 0.10
	13352	B	2,562 ± 129	6.43 ± 0.16

*The error expressed in the date reflects the identifiable uncertainties in hydration rim measurement; uncontrolled fluctuations in environment (especially temperature) and in chemical composition may in certain instances contribute additional error.

dates that are more recent than those derived from charcoal. Because obsidian is even more widespread than bone during this period, hydration dating can provide an independent assessment of bone apatite chronologies.

3) Amino acid racemization dating of East African materials has produced results that are difficult to resolve with regional successions, particularly at earlier time levels (*22*). Obsidian hydration dating provides an independent means of scaling these events. Since both techniques are temperature dependent, it should be possible to factor this variable out of the results by dating paired samples by each method. The results could provide important insights into the assumptions underlying each technique.

4) From earliest times, humans have littered the East African landscape with by-products from the flaking and use of stone tools. As a result, numerous terrestrial sedimentary deposits, among the most difficult to correlate geologically, can be dated with reasonable precision for the first time. Such deposits commonly interfinger with lacustrine and primary volcanic units and may be disrupted by faulting as well. Thus, hydration dating offers the possibility of more precise dating as well as correlating climatic, tectonic, and volcanic events over a wide area along the Gregory Rift.

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