OBSIDIAN-HYDRATION DATING, THE CONER PHASE, AND REVISIONIST CHRONOLOGY AT COPAN, HONDURAS

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The technique of obsidian-hydration dating contains great potentials for error, from both laboratory determinations of rate constants and measurements of effective hydration temperatures (EHTs) in the field. The rate constants used to determine these dates are of questionable validity and need to be independently verified. Significantly, no measurements of EHTs were taken at the site of Copán, Honduras, until the majority of the obsidian-hydration dates were calculated. An error of but a few Kelvins in estimated EHT can lead to dates that are in error by several centuries. In view of the likelihood of large errors in the Copán obsidian dates, the assertion that the Late Classic Coner phase should be extended beyond A.D. 900 (Webster and Freter 1990a) is premature.

La técnica de fechamiento por hidratación de la obsidiana tiene errores potenciales que resultan no sólo de determinaciones en el laboratorio de las constantes utilizados en la ecuación de Arrhenius sino también de las medidas de temperaturas efectivas para hidratación (TEH) en el campo. Las constantes utilizadas para determinar la fecha alargada de la fase Coner en el Clásico Tardío en Copán, Honduras, son de validez discutible y les falta verificación independiente. Además, ningún TEH ha sido medida en Copán. Un error de muy pocos grados Kelvin puede resultar en errores de varios siglos. Adicionalmente las fechas radiocarbónicas y arqueomagnéticas, y otros restos arqueológicos en este resumen no nos obligan a extender los límites generalmente aceptados de la fase Coner. A causa de la probabilidad de errores grandes en las técnicas utilizadas por Webster y Freter (1990a) para obtener las fechas nuevas en Copán, no existe suficiente evidencia para apoyar la tesis de que la fase Coner debe extenderse después de aproximadamente 900 D.C.

Recent studies of demography and settlement patterns at Copán have provided a wealth of new data, but they have also raised tantalizing questions. The most significant implication for Maya archaeology is that population decline in the Copán pocket and its hinterlands at the end of the Late Classic was slower than first thought, and that the Late Classic Coner phase continued well beyond the collapse of the elite political structure, to A.D. 1100 or 1200 (Webster and Freter 1990a). These new dates for the Coner phase are calculated from a large array of obsidian-hydration measurements. In order to assess the validity of this claim, it is necessary to review the current state of obsidian-hydration theory and the methods employed to generate the Copán dates.

THEORETICAL BACKGROUND

In recent years, the natural and artificial weathering of glass has been scrutinized by scientists interested in using glass to contain highly radioactive nuclear waste (e.g., Fillet et al. 1986; Hench et al. 1980; Shade and Strachan 1986; Spinoza and Means 1986; Strachan 1984; Umeki et al. 1986; Westik and Peters 1981; White 1986). In her masterful review of this body of literature, Tremaine (1989:13–14) has characterized the weathering of glass as consisting of four geochemical reactions: (1) The leaching of alkali ions (such as Na, Al, Mg, Ca, and K) from the glass into the liquid water or water vapor contacting it; (2) the replacement of these ions with H^+ or H_3O^+ ions from the liquid or vaporized solution by adsorption or diffusion; (3) the surface dissolution of the silica network of the glass; and (4) the precipitation of reaction products on the glass surface.

These reactions are not independent, and they all occur naturally when glass is in contact with liquid water or water vapor. Technically speaking, "hydration" refers only to the second reaction, but the first must co-occur in order for a hydration rind to develop. The third and fourth reactions

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are other weathering processes. They are important because they affect the apparent thickness of the hydration rind; the third reaction causes the surface of the glass to break down, hence the hydration rind is reduced, and the fourth causes the surface thickness of the glass to increase.

Various factors affect the rate at which glass, including obsidian, hydrates. These include the composition of the glass, effective hydration temperature (EHT), the relative humidity (RH) of the environment, the glass surface area-to-solution volume (SA/V), solution pH, solution composition, solution-flow rate, and even the exposure time (e.g., Clark et al. 1976; Ericson 1988; Mazer et al. 1991; Stevenson et al. 1989; Tremaine 1989). For a clear and thorough review of the technical literature that analyzes the effect of these factors on obsidian hydration, the reader is referred to Tremaine (1989).

In general, archaeologists have tended to ignore all of these factors except for glass composition (determined through trace-element analysis), EHT (determined through air-temperature or thermal-cell measurements), and RH (often measured using thermal cells) (e.g., Freter 1988; Mazer et al. 1991; Ridings 1991; Stevenson et al. 1989). What is particularly surprising is that pH has not been routinely measured. Soil pH measurements are easy to make and inexpensive. Furthermore, since it is widely recognized that hydration involves the replacement of alkali ions by hydrogen or hydronium ions (the first and second reactions), it should be apparent that pH is one of the most critical variables determining hydration rates.

While there is general consensus regarding the geochemical reactions that lead to hydration, and a growing awareness of the variables that influence hydration rates (e.g., Clark et al. 1976; Ericson 1988; Tremaine 1989), neither archaeologists nor geochemists can agree about how best to model hydration as a function of these variables, particularly time. Archaeologists have long debated how hydration-rind thickness should be expressed as a function of time. Radiocarbon or tree-ring dates have typically been used to support either a linear relation or a square-root relation (hydration-rind thickness in direct proportion to the square root of time [see below]), but other exponential relations between about one-third and one have also been proposed (e.g., De Atley and Findlow 1980; Ericson 1975, 1988; Findlow et al. 1982; Friedman and Trembour 1983; Hurtado de Mendoza 1981; Jackson 1984; Kimberlin 1976; Meighan 1983; Minor 1977; Tremaine 1989).

Geochemists are equally unsure of how to model the dependence of hydration-rind thickness on time. Tremaine (1989:35–45) summarizes several contradictory models; most seem to suggest that ultimately dependence on time is linear (e.g., White 1983), but by no means has a consensus developed. The confusion seems to be based on two points. First, after hydration begins, water is no longer reacting with pure glass, rather it is reacting with an already hydrated layer. A classic diffusion (square root of time) model breaks down at this point. Second, the different variables that determine the hydration rate interact in a synergistic fashion. Several researchers have observed a shift from a square-root relation (classic diffusion) between hydration-rind thickness and time to a linear relation, based on changes in pH (e.g., White and Claassen 1979; Wicks et al. 1982). In turn, pH, in a closed system, is influenced by *how long* hydration has occurred (Tremaine 1989). As alkali ions leach into solution and are replaced by hydrogen or hydronium ions (the first two reaction types), the pH of the solution will increase. An analogy with anthropological systems theory is useful; hydration is not a unilinear process, but one with many feedback loops between interacting variables. As such, it does not yield easily to simple modeling strategies. As two researchers note, "although simple rate expressions can be utilized to explain short-term lab-controlled dissolution of many silicate phases, their application to model natural weathering processes is much more difficult" (White and Claassen 1979:470). The Copán researchers (Freter 1988:104) attempt to use a simple diffusion expression with only two variables, time and EHT.

Because of the many problems in determining hydration rates, and the lack of consensus among both archaeologists and geochemists regarding how to model hydration, many scholars have chosen to use obsidian hydration as a relative-dating technique (e.g., Jonathon E. Ericson, personal communication 1991; Jackson 1986; Kaufman 1980; Origer 1987; Tremaine 1989, 1991; Tremaine and Fredrickson 1988; Trembour 1983; White 1984). In contrast, the Copán researchers, using rate constants and techniques espoused by Michels (1982, 1986; Michels et al. 1983), maintain that simple two-variable equations are adequate for developing a chronometric approach to obsidian-hydration dating. Furthermore, they assert that their approach produces dates that are "individually subject to a maximum random error of ± 70 years" (Webster and Freter 1990a:72).

The primary postulate of the dating technique used at Copán is that obsidian hydration can be modeled as a simple diffusion process (Freter 1988:104):

$$x^2 = kt \tag{1}$$

where x is the thickness of the hydration layer, k is the hydration rate, and t is the length of time the obsidian has been hydrating. Thus, the length of time the surface of a piece of obsidian has been subject to diffusion can be expressed as:

$$t = x^2/k \tag{2}$$

But k, the hydration rate, is not a constant. The Copán researchers modeled its dependence on temperature by using the Arrhenius equation (Freter 1988:104):

$$k = \mathrm{A}e^{-E/\mathrm{R}T} \tag{3}$$

where A is a constant, E is the activation energy, R is the gas constant (8.713 J/K-mol), and T is the temperature under which the obsidian is hydrated (in Kelvins).

Measurable hydration rinds can be obtained in the laboratory in a matter of hours or days, instead of centuries, because the rate of hydration k in Equation (3) is highly dependent on temperature. It is important to keep this in mind when reviewing the argument presented below.

The first step of the dating process is the determination of a hydration rate k_0 at a known temperature T_0. The hydration rate k_0 can be calculated by inducing the hydration of a piece of obsidian in a pressure-reaction vessel for a known period of time at a known temperature and then measuring the hydration layer and solving Equation (1) for k. In practice, this is usually done for several samples at different lengths of time. An average k_0 is then calculated through a linear-regression procedure (Michels et al. 1983:108). For Ixtepeque source obsidian, the type most frequently used at Copán, Michels (1982) determined a k_0 of 7.72 μ^2/day at a T_0 of 200°C, or 473.16 K. This value was used by Freter (1988:115) to determine the age of Copán obsidian specimens.

The activation energy E is also determined through induced-hydration experiments. Solving the Arrhenius diffusion equation (3), for ln k we obtain:

$$\ln k = -E/\mathrm{R}\,(1/T) + \ln \mathrm{A} \tag{4}$$

If we solve Equation (1) for k, and insert this expression into Equation (4), we get:

$$\ln (x^2/\mathrm{t}) = -E/\mathrm{R}\,(1/T) + \ln \mathrm{A} \tag{5}$$

Thus ln (x^2/t) is expressed as a linear function of $1/T$, and $-E/\mathrm{R}$ is the slope of that line. Here, several pieces of obsidian are hydrated at known but different temperatures for a constant amount of time t. The hydration rinds are measured, and the slope $-E/\mathrm{R}$ is determined through linear regression. Michels et al. (1983:108–109) advocate using temperatures ranging from 423.16 to 523.16 K (150–250°C) and a time t of four days. For Ixtepeque obsidian, an activation energy E of 87,423 J/mol was determined (Freter 1988:115; Michels 1982).

A general expression for the rate of hydration k *at any temperature* T can be derived from the Arrhenius equation:

$$k = k_0 e^{E(1/T_0 - 1/T)/\mathrm{R}} \tag{6}$$

Thus, for an archaeological sample, if the effective hydration temperature T is known, a hydration rate k can be calculated from Equation (6). This hydration rate, along with the measured rind thickness, can be inserted into Equation (2), yielding an age for the sample.

It is apparent, then, as Stevenson et al. (1989) point out, that the two most important factors influencing the accuracy of obsidian-hydration dating (assuming that this model has merit [see above discussion]) are the laboratory conditions under which E and k_0 are determined and the measurement of EHT T in the field. Mazer et al. (1991) add a third: the determination of the RH of cultural deposits from which obsidian is recovered.

Laboratory Techniques

The first factor, laboratory conditions, has been closely scrutinized in recent years. Stevenson et al. (1989:194–195) observe that at temperatures at or above 473 K, the rate of surface dissolution of obsidian is so great that it may exceed the hydration rate. Temperatures this high should, therefore, not be used during induced-hydration experiments. They also note, for similar reasons, that these experiments should not be done in deionized water, unless it is first saturated with silica (Stevenson et al. 1989:195). These observations are supported by results reported in Hench et al. (1980), Bates et al. (1988), and Tremaine and Fredrickson (1988). Mazer et al. (1991:510–511) add that similar experiments conducted with vaporized instead of liquid water must carefully match laboratory with site relative humidities. They conclude that hydration-rate constants (and hence, dates) vary (as a function of RH) by as much as 25 percent, with the majority of the shift occurring between 90 percent and 100 percent RH. Finally, Scheetz and Stevenson (1988:115–116) have studied the error in age dating caused by the optical limitations of the microscopes used to measure hydration rinds. They note that the single largest contributor to error is the determination of activation energy; if combined with other errors in the determination of rind thicknesses for establishing the hydration rate k_0 at high temperature and the measurement of hydration rinds on archaeological samples, the overall error is staggeringly large, ranging from -70 percent to $+33$ percent.

The experimental techniques used by Michels to determine the rate constants for Ixtepeque obsidian are described in two papers (Michels 1982; Michels et al. 1983). All of the critiques discussed above apply to his method. Experimental rate constants were determined in deionized water baths (therefore only at 100 percent RH) at temperatures as high as 523 K. The microscopes used for all measurements were of the type found by Scheetz and Stevenson (1988) to produce unacceptable error margins. The rate constants used to determine obsidian-hydration dates at Copán come directly from this early and uncorrected work (Freter 1988:113–115).

It is possible, in view of the methodological problems discussed above, that the experimental technique that determined the rate constants used for dating Copán obsidian has introduced systematic errors. These sources of error are introduced by independent measurements at different steps in the procedure. Although there may be some additive cancellation effect, it is still advisable that E and k_0 values for Ixtepeque obsidian be reconfirmed in the laboratory. Hydration-rind measurements of the samples recovered from Copán probably do not need to be checked because Freter (1988:119–120) has already estimated an error (± 70 years) for these measurements based on the resolution of her microscope and her ability to measure hydration-rind thicknesses. If new E and k_0 values are found to be significantly different from those determined by Michels (1982), however, new dates will have to be calculated from this data set.

Determining Effective Hydration Temperatures

Two methods are commonly used to determine the effective hydration temperature of a cultural deposit. The first, used at Copán (Freter 1988:113–114), is indirect and less accurate. In this technique, meteorological data from nearby weather stations are used to estimate mean yearly air temperatures for an archaeological site or, as in this case, an entire valley. Values are corrected using Lee's (1969) temperature integration equation and interpolation (and extrapolation) for different altitudes. Lee's formula is widely used, although no studies have addressed its applicability. A more rigorous thermodynamic approach to integrating air and soil temperatures is the use of harmonic-analysis techniques based on the Fourier heat-transfer equation (e.g., Bocock et al. 1977; Carson 1963). Unfortunately, no archaeologists have attempted this approach (Tremaine 1991:271).

In the case of Copán, EHTs were calculated for 50-m elevation intervals, ranging from 550 to 1,249 m asl (Freter 1988:117). The air-temperature method assumes that EHT varies only with altitude. Two sites at the same altitude should therefore have the same EHT, and no variations within the sites would be expected. In addition, because the sources of temperature data employed by Freter are distant, located in Guatemala (Freter 1988:113–114), her EHT values are only approximations, based on data of uncertain applicability. No attempt was made to verify these EHT values by taking direct measurements of soil (or even air) temperatures in the Copán region, where air and soil temperatures (and EHTs) of different microzones are influenced by factors such as shade, rainfall, and the reflective nature of the landscape.

The second method of determining EHTs involves making direct measurements using thermal cells (Ambrose 1976; Michels 1986). The cells are buried in the soil at the archaeological site. The cells are permeable to water vapor, which diffuses through their walls at a rate determined by soil temperature. After a full year (or years), the cells are retrieved and the amount of water absorbed by each cell is measured. EHTs are then calculated from these data. The elegance of this approach is that diffusion (of water into the thermal cells) is used to model hydration (assumed by Freter [1988:104] to be a diffusion process). Although the air-temperature method does not predict variation in EHTs from site to site (or within a site) at the same altitude, or temperature differences based on depth below the surface, the thermal-cell direct-measurement method does measure such differences. At the Coso volcanic field in California, Cleland (1990) observed a 2 K difference of EHT from 5 to 75 cm below the surface in the same profile. At Mungo, Australia, Ambrose (1984) measured differences in EHT of 1.2 K between depths of 5 cm and 1.5 m in the same profile. A similar study by Leach and Hamel (1984) in New Guinea documented a 3.2 K difference in EHT between 18 and 90 cm.

Intersite differences are equally of note. Ridings (1991) buried thermal cells at three prehistoric sites within the boundaries of the Fort Burgwin Research Center near Taos, New Mexico. The sites are within 1 km of each other; two are at an elevation of 2,255 m and the third at 2,279 m (Ridings 1991:Table 1). Her EHTs ranged from a high of 288.9 K at a depth of 5 cm below the surface at Pot Creek Pueblo to a low of 282.8 K at a depth of 75 cm at Cerrita (Ridings 1991:Figure 2). Thus, within a distance of less than one kilometer and over an elevation difference of 24 m, a range of 6.1 K in EHTs was documented. This range was observed well within the isoEHT elevation bracket of 50 m used at Copán (Freter 1988:117). Ridings buried 30 thermal cells in all (two at each depth). If more were used, and more sites within the area were tested to a greater depth, it is possible that the 6.1 K difference would have been even greater. At a depth of one meter, EHTs at all three sites had stabilized, but a difference of about 3 K was still observed from Pot Creek Pueblo to Cerrita (Ridings 1991:Figure 2). Ridings compared these experimentally determined EHTs with those predicted using the air-temperature method. After measuring the actual hydration rinds on artifacts recovered from the three sites, the two techniques yielded dates that differed by ca. 250 to 300 years (Ridings 1991:77, 82–83). We should recall that Webster and Freter (1990a), whose Copán dates are based on the air-temperature method, propose extending the Coner phase by exactly this margin.

A problem with both the air-temperature and thermal-cell methods is that current conditions (either air temperature or actual soil EHTs) are used to approximate the paleoenvironment (Ericson 1988; Tremaine 1989). While the use of measurements taken over multiple years can reduce error introduced by random fluctuations in annual temperatures, patterned change in climatic or depositional conditions cannot be determined using either method. Recent deforestation of the Copán region, for example, has probably raised EHTs (AnnCorinne Freter, personal communication 1992). In effect, the same problems that plague amino-acid racemization dating apply to obsidian hydration. Nevertheless, the thermal-cell technique, when used over multiple years, is clearly of more value than the air-temperature method because it measures actual, albeit current, EHTs rather than estimating them using Lee's equation, a formula of uncertain applicability. Furthermore, the thermal-cell method measures differences in actual EHTs that are not predicted using the air-temperature method. The weakness of the air-temperature method is that it is based on idealized conditions, while the strength of the thermal-cell technique lies in its concrete approach.

Effects of Relative Humidity on Hydration Dating

Recent research has also focused on the need to determine accurate RHs at archaeological sites (Mazer et al. 1991). Below a depth of 50 cm, soil relative humidities are often 100 percent (Mazer et al. 1991:510). But in upper levels, RH values of 80 percent to 85 percent are common. Under isothermal conditions, as noted above, Mazer et al. observe a 25 percent change (in final dates) as RH varies from 68 to 100 percent. The majority of this effect occurs as RHs range between 90 and

Table 1. Dating Errors Created by Faulty Estimated EHT Values (Calculated for Obsidian Buried in A.D. 800).

Elevation (m asl)	Freter's Estimated EHT (K)	Date (A.D.) Calculated if Freter's Estimated EHT is Off By						
		+3K	+2K	+1K	0K	−1K	−2K	−3K
550–599	297.98	1159	1052	933	800	651	484	298
600–649	297.78	1160	1053	933	800	650	483	297
650–699	297.59	1160	1053	934	800	650	483	296
700–749	297.40	1160	1053	933	800	650	482	295
750–799	297.20	1160	1054	934	800	650	482	295
800–849	297.00	1161	1054	934	800	649	481	294
850–899	296.81	1161	1054	934	800	649	481	293

100 percent (Mazer et al. 1991:510–511). When EHT and RH variation data from the Coso volcanic field are combined (2-K fluctuations in EHT, 68 to 97 percent RH), the hydration rate (and hence, dates) varies over nearly an order of magnitude (Mazer et al. 1991:511). It must be stressed that this extreme variation is based on measurements taken from the same 1-m profile!

The dating technique used at Copán ignores RH variation, largely because RH is not a variable expressed in the Arrhenius equation. The Copán researchers also may have assumed that the RH of tropical soils is always 100 percent. As an approximation, particularly for contexts deeper than 50 cm, this may be a reasonable assumption. But it should be tested, particularly at shallow depths, because the majority of the variability in hydration rates occurs between RH values of 90 and 100 percent. In this RH range, a 1 percent change in RH translates to approximately a 3 percent change in hydration rate (Tremaine 1991:273). Thus if blades from Copán were recovered from contexts with 90 percent RH, their final dates would be in error by approximately 30 percent (excluding all other sources of error).

MARGINS OF ERROR IN OBSIDIAN-HYDRATION DATES AT COPAN

To make the margins of error presented in the previous pages easier to comprehend, examples from Copán are presented below.

The first two columns of Table 1 present the elevation and estimated EHT values used to determine the age of Copán obsidian recovered from various elevations (derived from Freter [1988:Table 5.3]). The remainder of Table 1 displays the dates that would be calculated for blades *deposited in A.D. 800* if these estimated EHTs differ from actual EHTs by ± 1, ± 2, and ± 3 K. These dates are calculated using Equations (1), (2), and (6) and the values for k_0, E, and T_0 determined by Michels (1982) and used at Copán (Freter 1988:115). As the entries in Table 1 are calculated directly from values and equations used for dating the Copán obsidian, the only possible place where inaccuracy may be introduced is in the methodological assumptions employed by these researchers.

At an elevation of 550–599 m, Freter estimates an EHT of 297.98 K (Table 1). Let us assume that this estimated EHT is correct within a range of ± 3 K. How does this affect a blade buried since A.D. 800? In this case, the method used at Copán calculates a date somewhere between A.D. 298 and 1159. Thus an error margin of −502 to +359 years is generated (the error is not symmetrical because of the exponential term in Equation [6]). Even if the estimated EHT is correct to ± 1 K, the error margin is still −149 to +133 years.

We must also add the *independent* error margin of ± 70 years that Freter uses to estimate her accuracy in measuring hydration rinds. Thus an estimated EHT accuracy of ± 3 K yields an error margin of −572 to +429 years, and an estimated EHT accuracy of ± 1 K produces an error margin of −219 years to +203 years.

It is clear from Table 1 that even small inaccuracies in estimated EHTs can lead to errors in obsidian-hydration dates of several centuries. In evaluating the validity of the hydration dates from the Copán region, therefore, we must carefully assess the accuracy of the estimated EHTs.

The estimated EHTs used at Copán (derived from Freter [1988:Table 5.3]) may differ from actual EHTs for several reasons. First, as discussed above, the mean annual air temperatures (and their ranges) are not really known at Copán, but are based on data from comparable elevations, in what may be different ecological zones located in a different country. Second, judging from Ridings's (1991:Figure 2) thermal-cell data, we know that EHTs can range at least 3.2 K within a given soil profile and at least 6.1 K from one site to another at the same elevation. It is therefore reasonable to expect variations in EHTs of a comparable magnitude in the Copán region. Thus there is no logical reason to extend the Coner phase beyond A.D. 900 on the basis of these obsidian-hydration dates unless evidence is produced that demonstrates that the estimated EHT values used at Copán (derived from Freter [1988:Table 5.3]) are accurate within a range of less than ± 2 K.

The error introduced by inaccuracies in the predicted EHTs will not be immediately evident. If a collection of blades is found together (all subject to the same actual EHT), the error will be systematic, and their dates will cluster closely. If they are farther apart, and within the first meter or so of the surface, they may not cluster. Hence dates from different sites at the same altitude will have both systematic and random error attributable to inaccuracy of EHT prediction and local fluctuations in actual EHT (e.g., Ridings 1991). Thus, the Copán hydration dates probably do not form an internally consistent sequence, despite the seeming regularities in published charts (Webster and Freter 1990a:Figures 4, 10–11). Consequently, the obsidian-hydration dates probably cannot be aligned with any secure temporal framework. If they lack internal consistency, the obsidian-hydration dates cannot be used for relative dating or cross dating.

Figure 1 (based on Webster and Freter [1990a:Figure 4]) displays 1,904 of the obsidian-hydration dates generated by from Copán archaeological contexts. Not included are 90 dates determined from blades recovered from the surface and 54 dates deriving from sites above 900 m (the reason for this second exclusion is discussed below). This bar chart approximates a normal distribution, weighted somewhat on the side with the more recent dates. If we consider the modal date of A.D. 825 to represent an average date for this distribution (it closely approximates both the median and the mean), a curious question arises. Are all hydration dates generated at Copán estimates of this one central date, as the distribution suggests? The outermost vertical lines on Figure 1 represent the full range of error that would be created if Freter's estimated EHTs are actually off by ± 3 K (combined with the additional ± 70 years random error). In this case, more than 99.5 percent of the dates can be considered approximations of a mean date of A.D. 825. If her estimated EHTs are valid within ± 2 K, more than 96.1 percent of all the dates fall within the range of the second set of bars. Finally, if the estimated EHTs used at Copán are only off by the very small margin of ± 1 K, more than 86.4 percent of the dates can still be interpreted as approximations of a mean date of A.D. 825.

Freter, of course, used different estimated EHT values for different altitudes. In constructing Figure 1, an attempt has been made to minimize the difference in estimated EHTs between sites by using only dates from sites under 900 m in elevation. The estimated EHTs used at Copán (derived from Freter [1988:Table 5.3]) to determine rate constants for these elevations ranged from 296.79 to 297.98 K, or over a full range of 1.19 K. An average temperature of 297.39 K has been used to generate the error bars in Figure 1. Thus a potential for inaccuracy exists of up to ± .60 K in the positions of the error bars. But an error this large would only occur for dates derived from sites below 600 m or above 850 m in elevation.

Figure 2 is generated from the 609 obsidian-hydration dates from Gr. 9N-8 and Gr. 9M-22 (Freter 1988:310–317). In this case, the elevations of both groups are known to be 590 m (Freter 1988: 300). Thus the bars indicating error margins generated for ± 1, ± 2, and ± 3 K are not subject to error in their placement as described above. Figure 2 appears to have a mean and a median of about A.D. 800. Here an estimated EHT of 297.93 K was assumed (derived from Freter [1988: Table 5.3]). This determines a hydration-rate value of 5.96 μ^2/1,000 years (from Equation [6]). If this estimate is off by ± 3 K, all but about 1.5 percent of the dates can be considered as estimates of a central value of A.D. 800. If off by ± 2 K, the error bars generated account for more than 95 percent of the dates. Finally, if Freter's estimated EHT for 590 m is valid to within an error margin

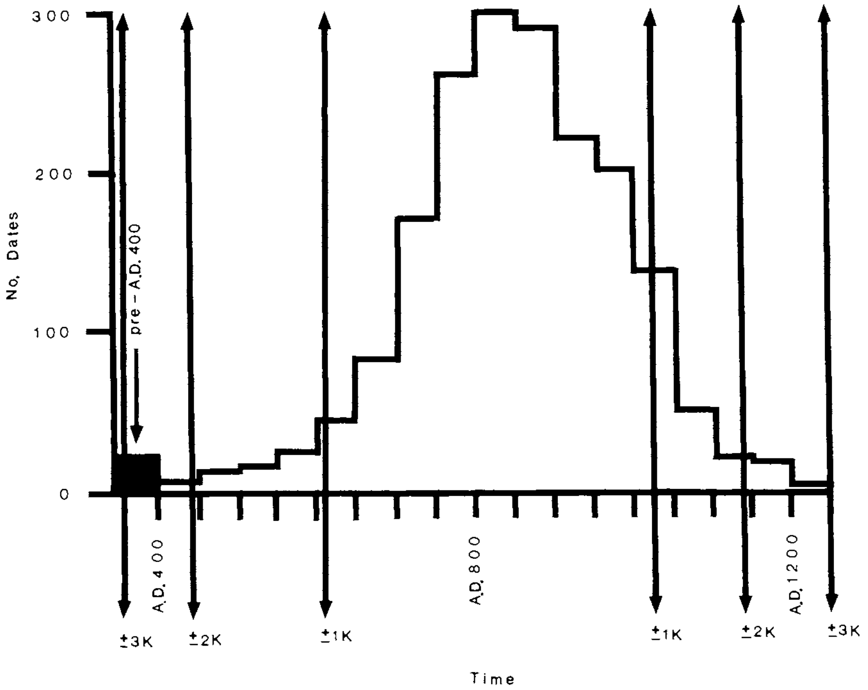

Figure 1. Hydration dates (n = 1,904) determined from obsidian recovered from the Copán region. Not included are dates derived from surface contexts and sites over 900 m. Vertical bars indicate the ranges of error (around a central date of A.D. 825) created by faulty estimates in EHTs combined with Freter's estimated ± 70 years random error. Following Webster and Freter (1990a:Figure 4), all dates before A.D. 400 are combined as a single category.

of ± 1 K, more than 79 percent of the dates can still be considered as estimates of a mean of A.D. 800.

It is clear that small errors in estimated EHTs cause very large margins of error for dates. We might conclude that the Copán hydration dates really approximate A.D. 800–850, a period close to the time of the elite collapse. I am not suggesting that all the obsidian blades were really buried about this time (which is clearly not true, as many dates are derived from pre-Coner contexts), but given the probable large error created by faulty estimated EHTs, this hypothesis is supported as well as any by the hydration dates. In other words, the dates could be used to *support* the conclusion that a full demographic collapse occurred during the early ninth century. The contention that the use of Coner phase ceramics extended into the twelfth century is therefore based on the analysis of what might be better considered extreme tail-end phenomena. Statistically it certainly makes great sense to exclude dates from either extreme of the distribution, unless they can be independently demonstrated to be valid (e.g., late dates associated with Postclassic plumbate ceramics or early dates associated with Middle Preclassic material).

During 1990 and 1991, E. W. Andrews V directed excavations in Copán Gr. 10L-2. Freter has processed 46 obsidian blades from these excavations, 28 of which come from contexts sealed by debris from the deliberate destruction of Str. 10L-32 between A.D. 800 and 950 (Andrews and Fash 1992:Table 2). All of these blades were chosen for dating because of their clear provenience; they come from undisturbed middens and not from architectural fill or collapsed debris. Although the majority of the obsidian dates do approximate a date later than A.D. 800, 21 percent fall before A.D. 730 (one 70-year "maximum random error" [Webster and Freter 1990a:72] margin before A.D. 800), 11 percent are more than two "error margins" before A.D. 800, and 7 percent deviate

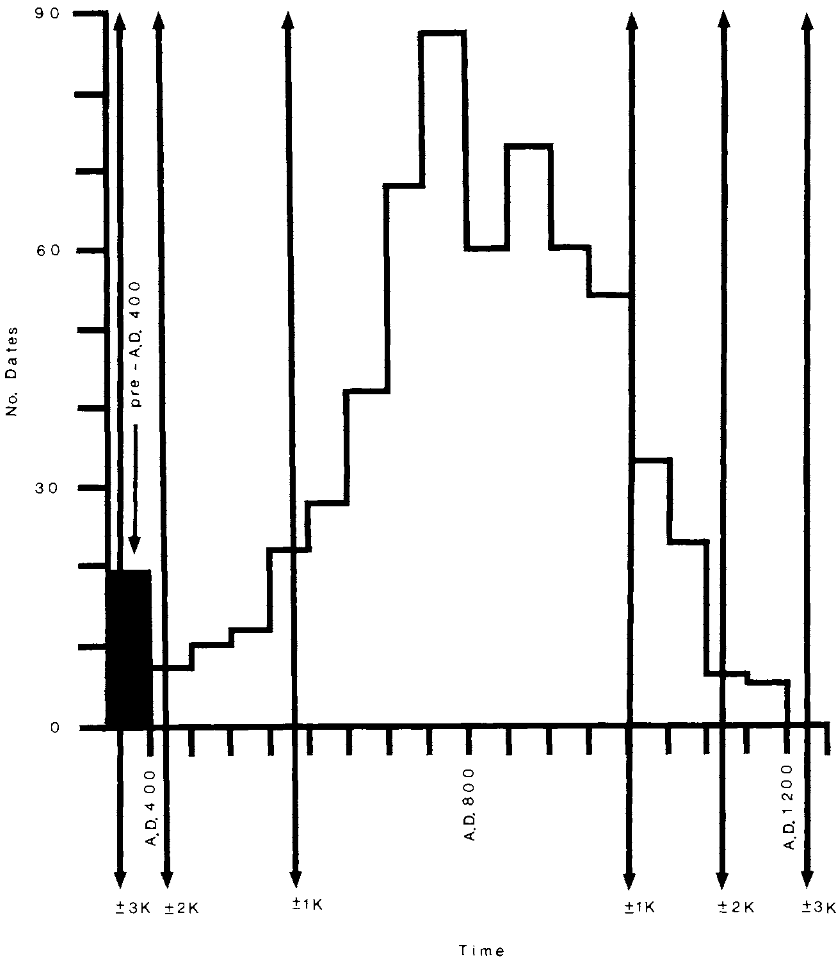

Figure 2. Hydration dates (n = 609) determined from obsidian recovered from Gr. 9N-8 and Gr. 9M-22, both at an elevation of 590 m. Vertical bars indicate the ranges of error (around a central date of A.D. 800) created by faulty estimates in EHTs combined with Freter's estimated ± 70 years random error. Following Webster and Freter (1990a:Figure 4), all dates before A.D. 400 are combined as a single category.

by three or more "error margins" from that date. Three dates (A.D. 272 ± 70, A.D. 469 ± 70, and A.D. 645 ± 70), determined from blades recovered from a small midden immediately in front of Str. 10L-234, are particularly disturbing. The context of this midden is impeccable. It lies immediately above an undisturbed plaster floor constructed during the Coner phase, and below wall fall from Str. 10L-32. If accepted as accurate, these dates suggest that the Coner phase began hundreds of years earlier than previously thought. But internal site stratigraphy, radiocarbon dates, inscriptions, and even other obsidian-hydration dates from Gr. 10L-2 all demonstrate that this midden cannot be this old.

A logical conclusion is that a significant percentage of the obsidian dates from Copán may be in error. Only 2 percent of the Copán obsidian dates fall after A.D. 1100, and just 12 percent are more recent than A.D. 1000 (Webster and Freter 1990a:Figure 4). Given that 11 percent of the obsidian-hydration dates determined from assemblages sealed by the destruction of Str. 10L-32 after A.D. 800 are in error by at least two 70-year "error margins," and the fact that dates can be in error by at least 528 years (in the case of the date of A.D. 272 ± 70 years), the assertion that the Coner phase should be extended to A.D. 1100–1200 seems unsupported. Furthermore, the notion that "dates are individually subject to a maximum random error of ± 70 years" (Webster and Freter 1990a:72) is clearly inaccurate.

It is possible that many of the dates derived from obsidian-hydration data are coincidentally accurate. In some contexts, the estimated EHTs used at Copán may be correct. This may explain the agreement of one obsidian-hydration date of A.D. 777 ± 70 years with a radiocarbon date of A.D. 740 ± 90 years (ETH-4499) derived from a closely associated sample (Webster and Freter 1990a:78). On the other hand, Webster and Freter (1990a:78) dismiss most radiocarbon dates from Copán as having "a nonrandom bias." Perhaps, then, this date, too, is biased, and an inaccurate obsidian-hydration date just happens to seem to agree with it.

Webster and Freter (1990a:78–79) claim that their sequence is aligned properly because, in a preliminary analysis, it yields accurate dates for the Acbi/Coner transition. In particular, they state that 24 hydration dates determined from obsidian recovered from a single-mound site (34A-12-2) and its associated field hut (34A-12-1) ranged from A.D. 614 to 723 (Webster and Freter 1990a: 78). The associated ceramics were transitional Acbi/Coner. It is quite possible that Freter's estimated EHT for this site nearly approximates the correct value, and that local soil temperatures do not vary greatly. But we have seen that the internal consistency of the overall sequence of hydration dates is highly suspect. Therefore, any attempt to align the sequence with any secure temporal framework on the basis of some correct dates may be misguided.

INDEPENDENT EVIDENCE FOR THE EXTENSION OF CONER

What other evidence, if any, supports an extension of the Coner phase into the twelfth century?

Thirteen radiocarbon dates were determined during Phase 1 of the Proyecto Arqueológico Copán (PAC) and are still the only dates that have been published (Viel 1983:545). Only two are later than A.D. 580 ± 100 (from a Middle Classic Acbi context); these two, A.D. 1070 ± 60 (UCLA-2311 G) and A.D. 1340 ± 60 (UCLA-2311 H) come from Middle Preclassic Uir contexts, and are most certainly either inaccurate or derived from intrusive carbon samples. It should be noted that Viel does not indicate whether these dates are calibrated or not.

Webster and Freter (1990a), among others, believe that a systematic bias exists in a great many of the radiocarbon dates from Copán excavations. Specifically, a consensus is developing among researchers at Copán that many of the ages determined from carbon samples are too great by as much as two centuries. Phase II of PAC has generated 10 radiocarbon dates, none later than A.D. 740 ± 90 (ETH-4499) (David Webster, personal communication to E. Wyllys Andrews V 1990). Even if adjusted forward by 200 years, and pushed to the edge of its margin of error, this date would not reach into the twelfth century. Besides, this radiocarbon date is the one that is used to support the obsidian-hydration-dating method (Webster and Freter 1990a:78). Of another 19 radiocarbon dates, determined more recently from Strs. 10L-16 and 10L-26 and from the Late Classic Gr. 10L-2 at the south edge of the Acropolis, all but two fall before A.D. 700 (E. Wyllys Andrews V, personal communication 1991). The reported age for one, 1,180 ± 50 years (Beta-40306), translates to a calibrated date of A.D. 780 (880) 895. This date, however, like ETH-4499, is thought to be accurate because it coincides closely with the estimated age of the cultural material found within the same level. The other late date is derived from a radiocarbon age of 1,250 ± 90 years (Beta-40312) and translates into a calibrated date of A.D. 666 (772) 886. It is compatible with the estimated age of the level in which the carbon sample was found, but probably should be earlier since an earlier date was determined from carbon recovered directly above. Again, even if these two dates are pushed forward two centuries their error margins would not reach into the twelfth century.

Most of these 42 radiocarbon dates are from cultural deposits that would not be expected to yield twelfth-century dates and so form a biased sample. These dates, nevertheless, do not support a twelfth-century extension of the Coner phase; Coner phase ceramics have not yet been associated with twelfth-, or even tenth-century radiocarbon dates.

Two of the 17 archaeomagnetic dates mentioned by Webster and Freter (1990a) have been published in PAC reports. They are A.D. 520 ± 20 (or A.D. 550–565) and A.D. 575 ± 17, and come from Middle Classic Acbi contexts (Viel 1983:548). Three more archaeomagnetic dates are presented in Freter's (1988:313) dissertation: A.D. 540 ± 30 years, A.D. 830 ± 30 years, and A.D. 510 ± 30 years; these are not relevant to an extension of the Coner phase into the twelfth century. The seven obsidian-hydration dates determined from the same contexts as these three archaeomagnetic dates are systematically about 100 years more recent. In one case, three hydration dates of A.D. 660, 622, and 631 were determined from obsidian blades recovered below a clay floor yielding the archaeomagnetic date of A.D. 510 (Freter 1988:313). Thus, the archaeomagnetic dates appear incompatible with the obsidian-hydration dates. This suggests that there may be systematic errors associated with either the hydration or archaeomagnetic dates, or both.

Wolfman (1990:Table 15.4) has recently revised four of these archaeomagnetic dates and published them, along with two others. They are A.D. 510–570 (CO100), A.D. 560–585 (CO102), A.D. 835–865 (CO183), A.D. 495–570 (CO185), A.D. 275–325 (CO186), and A.D. 575–600 (CO188). The first four are revisions of the dates published by Viel (1983:548) and two of those presented in the dissertation (Freter 1988:313).

The mesoamerican polar curve after A.D. 900 is poorly understood. Only five post-A.D. 900 dates from Mesoamerica have been published: three from Lambityeco and two from Tula (Wolfman 1990:Table 15.1). One unpublished archaeomagnetic date from Copán may be later than A.D. 900 (or alternatively may date to just before A.D. 700), but until the polar curve for this time period is clear, it seems wise to draw no conclusions (Daniel Wolfman, personal communication 1991).

Pollen studies (Abrams and Rue 1988; Rue 1986, 1987) do seem to support the argument that some inhabitants remained in the Copán region into the Early Postclassic. Very small quantities of maize pollen were found at two positions in a 135-cm core from the Petapilla swamp, between carbon samples yielding dates of A.D. 1010 ± 60 and A.D. 1355 ± 70 (Abrams and Rue 1988: Figure 2; Rue 1987:285). No maize pollen, however, was found in the bottom 15 cm of the core, dating to approximately the first half of the eleventh century. A large agricultural population is only demonstrable from maize-pollen data in the uppermost 45 cm of the core, which probably date to A.D. 1500 or later. Low levels of arboreal pollen from the bottom 35 cm of the core suggest that extensive reforestation in the Copán region did not begin until sometime around A.D. 1200 (Abrams and Rue 1988:Figure 2; Rue 1987:Figure 2b). But to what extent does retarded regrowth necessitate a large population? And might these two radiocarbon dates be systematically biased as well? These and other questions need to be answered before palynological data can be said to support the accuracy of obsidian-hydration dates. Rue's (1986) excellent study, however, does support the position that the recovery from the environmental damage caused by Classic period land-use strategies took a long time.

It has never been thought that the Copán region was totally abandoned immediately following the elite collapse, some time after A.D. 822. Small amounts of Tohil Plumbate pottery have been found, particularly in the area referred to as El Bosque, to the southwest of the Acropolis. Tohil Plumbate is a diagnostic for Early Postclassic occupation throughout the Maya area. The Coner phase sites with late hydration dates should have at least some Tohil Plumbate ceramics, but they do not. Ejar phase plumbates have not been found far from the site center (Fash and Sharer 1991: 184).

One possible explanation for the limited distribution of Tohil Plumbate in the Copán region is that after ca. A.D. 900 population levels were low, and tended to be centered near the old elite center. Another is that Tohil Plumbate, probably an elite trade item, is found only in those areas of the Copán Valley where elite activity continued into the Early Postclassic. The first hypothesis is inconsistent with the obsidian-hydration dates and settlement data, and the second raises questions about the collapse of the elite hierarchy at Copán.

Sheehy (1991:15), in a chronological assessment of the construction episodes of Patio Gr. 9M-22-A, discusses the association of 21 plumbate sherds, apparently from the same vessel, with dated obsidian blades. He attributes three early dates (A.D. 737, 770, and 783) to older blades incorporated into later fill. The later associated dates, A.D. 1105, 1086, and 1074 (from the lower levels of the excavation unit), and A.D. 1018 (from the uppermost stratigraphic level) are more problematic. First, as he notes, an earlier date appears above later dates. Second, while these dates might fit well with Early Postclassic Tohil Plumbate, they are associated with "Late Classic Robles/San Juan

Plumbate" sherds (Sheehy 1991:15). Although the taxonomic status of Robles Plumbate is uncertain, it is contemporary with San Juan (Neff and Bishop 1988:515–517), and the plumbate sherds recovered from Patio Gr. 9M-22-A are Late or Terminal Classic. Outside of the Soconusco region, San Juan Plumbate occurs no later than about A.D. 950. If the obsidian-hydration dates from Copán are accurate, the ceramic chronologies for many other sites may need to be realigned (e.g., Brown 1978; Culbert 1965; Lee 1978; Lowe and Mason 1965; Lowe et al. 1982; Parsons 1967–1969; Shook 1965). The obsidian-hydration dates from Patio Gr. 9M-22-A have ramifications that extend far beyond Copán.

Is Coner phase pottery found outside of the Copán region in assemblages dating after A.D. 900? The answer appears to be no. Although elite Coner wares such as Copador and Gualpopa are commonly found at Late Classic sites in western El Salvador, none have been reported at Early Postclassic sites (e.g., Amaroli 1986; Boggs 1943, 1945, 1950, 1962, 1963; Fowler 1981, 1989; Sharer 1978; Sheets 1984). Thus there is no evidence from beyond the Copán region that supports an extension of the Coner phase into the Postclassic.

Sheehy's (1991) excavations in Patio Gr. 9M-22-A suggest that only utilitarian wares were produced in the Copán region after about A.D. 925. His last two "Time Spans" (defined vertically by stratigraphic position and horizontally by lateral connections between architectural units) have 11 associated hydration dates ranging from A.D. 919 to 1018 (Sheehy 1991:Figure 15). Virtually no polychromes, including Coner phase diagnostics such as Copador and Gualpopa, were recovered from Time Span 1 and 2 contexts at Patio Gr. 9M-22-A (Sheehy 1991:13).

In summary, the distribution of universally recognized Early Postclassic ceramics (such as Tohil Plumbate) at Copán is quite limited. Furthermore, Coner phase wares are not found in association with Postclassic diagnostics at sites beyond the Copán region. Evidence from Patio Gr. 9M-22-A does not support the assertion that Coner elite wares were used after about A.D. 925. Finally, hydration dates associated with "Robles/San Juan" Plumbate sherds recovered from Patio Gr. 9M-22-A conflict with ceramic chronologies developed at other sites. Although late obsidian-hydration dates have been determined for some Copán assemblages containing Coner phase diagnostics such as Copador, the most parsimonious explanation seems to be that these dates are inaccurate.

Epigraphic evidence for the continuation of the Coner phase into the twelfth century of course does not exist. No line of argument that is independent of the obsidian-hydration dates supports the conclusion that the Coner phase should be extended for another two to three hundred years.

CONCLUSIONS AND SUGGESTIONS

Although the accuracy and precision of the Copán obsidian-hydration dates are suspect, other aspects of the settlement study are of immense value. We now know a great deal about the demography of greater Copán, largely due to the work of Webster and Freter (1990b; Freter 1988). Webster and Gonlin (1988) have also contributed significantly to our knowledge of how the "humblest Maya" lived at Copán. But population estimates for the Late Classic need to be reconsidered. If the terminal date of the Coner phase cannot be pushed to A.D. 1100 or 1200, many more sites are contemporaneous than Webster and Freter (1990a, 1990b) believe, and Late Classic population levels in the Copán region may have been substantially higher than they estimate.

Although a wide range of data has been employed here to cast doubt on the validity of the obsidian-hydration dates, there are four fundamental issues. First, the lack of agreement among both archaeologists and geochemists on how to model hydration suggests that obsidian-hydration dating, in its present form, should probably not be relied upon as a chronometric technique. Second, the model espoused by Michels (1982, 1986; Michels et al. 1983) and used by the Copán researchers ignores many variables that influence hydration rates. Third, serious errors may have been introduced during the experimental determination of rate constants. Finally, and most critical from the point of view of the field archaeologist, the estimated EHTs employed at Copán (Freter 1988:113–118) are suspect. I have demonstrated that very small margins of error in EHTs (on the order of one or two Kelvins) lead to dates that are incorrect not by decades, but by centuries. This conclusion is derived solely from the equations used at Copán to model hydration. If these dates are to be accepted as accurate, the estimated EHTs must be empirically demonstrated to have associated errors certainly less than two Kelvins, and probably less than one. Until physical measurements verify the asserted but undemonstrated accuracy of the estimated EHTs employed by Copán researchers, it seems prudent not to revise drastically our interpretations of the Late Classic Coner phase and the Maya collapse at Copán.

Nevertheless, the assertion that a demographic collapse at Copán was not contemporaneous with the disintegration of the elite political system has merit. As Fash and Sharer (1991) suggest, it is more profitable to consider the collapse of Copán as a series of processes beginning with the decentralization of authority during the eighth century and ending with abandonment sometime after A.D. 900. As mentioned above, the presence of trace amounts of Tohil Plumbate near the site center is adequate proof that populations, however small, continued to live in, or at least visit, Copán well into the Early Postclassic period. For reasons discussed here, however, the assertion that population levels remained substantial until A.D. 1000 or so, and that Coner phase ceramics (particularly the polychromes) were produced well into the Early Postclassic, is not adequately demonstrated by the hydration dates. At present it seems more prudent to continue to use Viel's (1983) ceramic chronology, which, after all, defines the Coner phase as extending beyond the elite collapse, until about A.D. 900. Ultimately it may prove more advantageous to redefine the Coner phase, but until the validity of the obsidian-hydration dates is demonstrated, or independent lines of evidence supporting an extension are found, a major change in chronology is unwarranted.

Can the validity of the obsidian-hydration dates be tested empirically? As these dates have been determined from documented contexts, it is possible that accurate EHT measurements for at least some contexts can be made. In 1988 and 1989, after more than 2,000 hydration dates had already been processed, an attempt was made to verify estimated EHTs at Copán. Thermal cells were buried at three elevations on the valley floor and up the surrounding slopes (Webster and Gonlin 1988: 183). Preliminary results contrast sharply with estimated EHTs determined using the air-temperature method. At 590 m, an estimated EHT of 300.0 ± .2 K was calculated from thermal-cell data. This contrasts with an air-temperature-estimated EHT of 297.89 K. Thus there is a discrepancy between the two measurements of about 2.1 K. AnnCorinne Freter (personal communication 1992) believes that this thermal-cell-estimated EHT is far too high, largely because it was determined under full sun conditions. She quite reasonably argues that most sites in the Copán region have been shaded since the thirteenth century, and thus only thermal-cell measurements from shaded areas should be used for estimating EHTs.

A second thermal-cell measurement was made at 690 m under shaded conditions. At this elevation, a thermal-cell-estimated EHT of 297.0 ± .2 K seems to agree with the air-temperature-estimated EHT of 297.49 K (AnnCorinne Freter, personal communication 1992). But given Ridings's (1991: Table 1) observation of a 6.1-K difference in EHTs within an elevation range of only 24 m, it would be premature to say that this single thermal-cell measurement from Copán supports the air-temperature method.

A final estimated EHT of 295.2 ± .2 K was calculated from thermal-cell data collected in a shady area at 900 m. This differs from the air-temperature-estimated EHT of 296.70 K by approximately 1.5 K. While 1.5 K may not seem very significant, the two estimated EHT values produce dates differing by almost 200 years (for a blade actually deposited in the ground in A.D. 800)!

It was decided that the thermal-cell-estimated EHTs would not be used to calculate hydration rates at Copán for three reasons (AnnCorinne Freter, personal communication 1992). First, only three measurements were made. Second, thermal-cell data were collected over a time span of only one year. Third, recent deforestation at Copán has probably raised EHTs. While tropical soil temperatures are relatively stable, it is quite possible that the thermal cell EHTs determined for 1988–1989 are not representative of the entire time span since deposition. In other words, 1988–1989 may not have been a year that best approximates the actual paleoclimate. In contrast, the air-temperature EHTs were calculated using data collected over 27- and 16-year time periods (Freter 1988:113–114). However, long-term changes in paleoclimate would also tend to be ignored using the air-temperature method. Furthermore, as stated above, the air-temperature data were not even collected in the Copán region.

An ongoing research program is clearly needed to answer chronological questions at Copán. First, and perhaps most important, problems with radiocarbon dating in the Copán region need to be resolved. Second, air-temperature measurements should be made at various elevations on a daily basis. These could be used not only to test the applicability of the Guatemalan data to Copán, but also the air-temperature method. Third, thermal cells should be used to measure EHTs in documented contexts. It must be remembered, however, that thermal-cell determinations of EHTs apply only to the particular cultural deposits in the sites where the measurements have been made. Furthermore, measurements taken from unshaded contexts may be suspect. Both air-temperature and thermal-cell measurements of EHTs may need to be collected over a long period, perhaps 10 or 20 years, before enough data are accumulated to accurately estimate paleoEHTs. Fourth, some measurements of soil RHs, pHs, cation-exchange capacity, ionic composition and iron concentration of soil moisture, and ground-water flow rates should be attempted (Ericson 1988; Tremaine 1989). Fifth, the rate constants determined by Michels (1982) should be independently checked, not only through induced-hydration experiments, but also through empirical comparisons with radiocarbon data from Copán and other sites where Ixtepeque obsidian is found. From accurate EHT measurements and verified rate constants, it would be a simple task to recalculate age determinations.

An alternative and less time-consuming approach would be to use the hydration measurements to form a relative sequence that could be loosely tied to the ceramic chronology through the use of associated radiocarbon and archaeomagnetic dates. The problems with radiocarbon dating at Copán have already been discussed. Also, as noted above, the internal consistency of such a sequence may be suspect because of the applicability of different actual EHTs to different archaeological contexts. If variability in actual EHTs is more than 2 or 3 K, it may be necessary to divide the hydration-rind measurements into sets where actual EHTs (determined using thermal cells) are relatively constant. Internal consistency would be more likely in these isoEHT subsequences. This approach, however, still ignores the effects of variables such as RH, pH, and water-flow rates on hydration rates.

Webster and Freter (1990a:70–71) note that obsidian-hydration dating has produced "mixed results in Mesoamerica." It must be stressed that as an absolute-dating technique, obsidian hydration is still in its infancy. A valuable lesson can be learned from an analogy with radiocarbon dating, a technique that is now almost a half-century old. Large sources of error in radiocarbon dates are still being discovered (e.g., Bard et al. 1990a, 1990b; Kerr 1990; Levi 1990; Monastersky 1990). At Copán, researchers are at a loss to explain discrepancies between radiocarbon dates and the ceramic chronology, yet no one has seriously suggested that the Coner phase should be redefined on the basis of these dates. The slavish devotion to the accuracy of radiocarbon dates has led to great errors of interpretation in the past (Andrews and Hammond 1990) and undoubtedly will continue to cause errors in the future. It would be rash to think that the obsidian-hydration technique is not subject to problems of the same magnitude as those associated with radiocarbon dating.

A better approach to absolute dates is to consider them not as answers to temporal questions, but as data that need to be interpreted. The Copán hydration data should be considered along with all other independent sources of chronological information. The obsidian-hydration data used to extend the end of the Coner phase are not currently supported by radiocarbon, archaeomagnetic, ceramic, or epigraphic data, and are not strongly supported by palynological data (dated by association with carbon samples). Because the pitfalls of the relatively new technique of obsidian-hydration dating are only now beginning to be understood, we must use it with caution.

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