High-resolution chronology for the Mesoamerican urban center of Teotihuacan derived from Bayesian statistics of radiocarbon and archaeological data

Laura E. Beramendi-Orosco a,⁎, Galia Gonzalez-Hernandez b, Jaime Urrutia-Fucugauchi b, Linda R. Manzanilla c, Ana M. Soler-Arechalde b, Avto Goguitchaishvili d, Nick Jarboe e

a Instituto de Geología, Universidad Nacional Autonoma de Mexico, Ciudad Universitaria, Mexico D.F. 04510, Mexico
b Instituto de Geofísica, Universidad Nacional Autonoma de Mexico, Ciudad Universitaria, Mexico D.F. 04510, Mexico
c Instituto de Investigaciones Antropológicas, Universidad Nacional Autonoma de Mexico, Ciudad Universitaria, Mexico D.F. 04510, Mexico
d Laboratorio Interinstitucional de Magnetismo Natural, Instituto de Geofísica, Sede Michoacan, Universidad Nacional Autonoma de Mexico, Campus Morelia, Michoacan, Mexico
e University of California-Santa Cruz, Earth and Planetary Sciences Department, 1156 High Street, Santa Cruz, CA 95064, USA

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A B S T R A C T

A high-resolution 14C chronology for the Teopancazco archaeological site in the Teotihuacan urban center of Mesoamerica was generated by Bayesian analysis of 33 radiocarbon dates and detailed archaeological information related to occupation stratigraphy, pottery and archaeomagnetic dates. The calibrated intervals obtained using the Bayesian model are up to ca. 70% shorter than those obtained with individual calibrations. For some samples, this is a consequence of plateaus in the part of the calibration curve covered by the sample dates (2500 to 1450 14C yr BP). Effects of outliers are explored by comparing the results from a Bayesian model that incorporates radiocarbon data for two outlier samples with the same model excluding them. The effect of outliers was more significant than expected. Inclusion of radiocarbon dates from two altered contexts, 500 14C yr earlier than those for the first occupational phase, results in ages calculated by the model earlier than the archaeological records. The Bayesian chronology excluding these outliers separates the first two Teopancazo occupational phases and suggests that ending of the Xolalpan phase was around cal AD 550, 100 yr earlier than previously estimated and in accordance with previously reported archaeomagnetic dates from lime plasters for the same site.

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Introduction

One of the problems encountered by radiocarbon dating is that when calibrating from the radiocarbon to the calendar scale, the resulting calibrated date may cover a long period, even longer than the original associated uncertainty in 14C yr. This is a consequence of the analytical precision of the radiocarbon determination and the shape and uncertainty of the calibration curve. There are periods in which the calibration curve has plateaus or has pronounced wiggles resulting in larger or multiple calendar intervals, even for radiocarbon determinations with high analytical precision (Guilderson et al., 2005; Blackwell et al., 2006).

The low precision obtained when calibrating radiocarbon dates individually makes the construction of archaeological chronologies difficult, as sometimes samples from different occupation phases lie within the same calendar interval. However, generally archaeologists have several samples from the excavated site, and also additional information related to the context where each sample was recovered, such as the pottery associated, stratigraphy or construction level, and historical information. Accordingly, it is possible to apply Bayesian statistics integrating the radiocarbon data and the a priori archaeological information in order to improve the precision of the calibrated dates. Full use of available information from dating and archaeological study provides a chronology with improved resolution, making it possible to differentiate occupations or periods for the excavated site. The use of Bayesian statistical models for the construction of chronologies has gained importance in the last years, and archaeology is one of the main disciplines applying these tools in the generation of chronologies incorporating chronometric data and other chronological information (Buck et al., 1991; Buck and Christen, 1998; Buck, 2004). For a detailed Bayesian radiocarbon calibration framework see Buck (2004) and references therein.

In this work we report the results of applying Bayesian statistics to build a high-resolution chronology for Teopancazco, an extensively excavated and studied site in the Teotihuacan Valley, Central Mexico. Teopancazco is a neighborhood compound in the southeastern sector of Teotihuacan, characterized by four constructive phases built during the Classic (AD 200–600/650), Epiclasic (AD 650–900), and Aztec (AD 900–1521) times.

Teotihuacan is one of the most studied sites in Mesoamerica due to its political importance during the Classic period; however, its last years
and the process of its abandonment are still a debate amongst the archaeological community (Manzanilla, 2006, 2003c). For this reason, the need of a high-resolution chronology has gained importance in order to help elucidate when and why this city was abandoned.

What prompted us to make use of a Bayesian model in calibrating the radiocarbon dates for Teopancazco was that, although there was a significant amount of samples coming from well-defined contexts, when performing the calibration individually most samples covered a period of a few hundred years, making it difficult to differentiate occupational phases, mainly due to the part of the curve having either pronounced wiggles or plateaus (Fig. 1).

**Methods**

**Archaeology of the site**

Teotihuacan, located in the Basin of Mexico, was one of the most important urban centers of Mesoamerica during the Classic period (AD 200–650), covering a surface of about 20 km².

The Tlamimilolpa phase (formerly dated by AD 200–350) is the first phase of urban planning at Teotihuacan, when the urban grid was set with domestic life in multifamily apartment compounds (Millon, 1973). In the southeastern sector of the City a large surface of what will be named as Teopancazco was first occupied on top of alluvial soil. The compound grew particularly in its northeastern sector around a main activity area set to the east of the ritual plaza (Manzanilla, 2006).

The transition between Tlamimilolpa and Early Xolalpan (c. AD 350) at Teopancazco is related to a set of termination rituals (Manzanilla, 2002), which are ceremonial activities to put an end to political core of the City, particularly along the Street of the Dead, which may be correlated to the fire of the central sector of the city, despite the difference with the archaeomagnetic dates reported by Wolfman (1990).

### Table 1

<table>
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<tr>
<th>Sample Laboratory code</th>
<th>Description</th>
<th>Type of analysis</th>
<th>(^14)C yr BP ± 1\sigma</th>
<th>Bayesian model group</th>
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<td>Transition</td>
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<td>AMS</td>
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<td>Early Xolalpan</td>
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**Footnotes:**

4 UCA: Center for Applied Isotope Studies, University of Georgia; Beta: Beta Analytic Inc.; CAMS: Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory.

6 LSC: Liquid Scintillation Counting; AMS: Accelerator Mass Spectrometry.

7 Determinations treated as one sample by means of a pooled mean.
During the Metepec phase (formerly dated by AD 650–750 by Rattray (1991) and AD 550–650 by Manzanilla (2003b)) the city’s political and administrative institutions no longer existed, and little by little, the city was depopulated, and reoccupied by newcomers from the Bajío region in Western Mexico.

Teopanaczco has been extensively excavated, with the first excavation led by Leopoldo Batres in 1884. This first excavation was performed around the room where the famous mural painting of Teopanaczco was found, in the southern portion of the compound exposed (Cabrera, 1995). Batres exposed a series of rooms, part of the central courtyard and eastern temple. The altar was partially destroyed in its western section, and many of the finds originally set inside it were found to the east. The subsequent excavations were performed between 1997 and 2005 as part of the long-term interdisciplinary project “Teotihuacan: Elite and Government” led by Linda R. Manzanilla.

Sample collection and analysis

Samples were collected during 13 archaeological excavation field seasons carried out from 1997 to 2005. Dated samples were charred wood from hearths used for offerings, termination rituals, or other activity areas. In addition, five samples from charred wooden beams and columns from a collapsed ceiling were also dated (Manzanilla, 2003a,b, 2006). The dating of samples from large wood beams was performed because it was considered that these could help to estimate when the building of the site had started, despite the problem of inbuilt age associated to dating this kind of samples (McFadgen et al., 1994). Samples are detailed in Table 1.

Radiocarbon analyses by liquid scintillation spectrometry were performed at Beta Analytic (Beta, 10 samples) and University of Georgia (UGA, 3 samples). In addition, ten small-sized samples were analyzed by AMS at Beta Analytic and 10 samples were analyzed by the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory (CAMs).

Calibration

Individual calibrations of radiocarbon dates were carried out using the Calib 5.0 program (Stuiver et al., 2005) and the online BCal program (Buck et al., 1999, 2001) with the INTCAL_04 calibration data set (Reimer et al., 2004).

Calibration with Bayesian analysis was performed using the online BCal program (Buck et al., 1999, 2001). Samples were arranged in groups by occupational phases according to the architecture and the pottery associated with each one. A probability of 5% of being outliers was assigned to all samples in order to identify outliers. Reported intervals correspond to high-probability regions at the 95% level. Reproducibility was checked by calibrating each Bayesian scenario a few times.

Bayesian models

The 33 radiocarbon ages are arranged in four groups according to three occupational phases and one transition (there are no radiocarbon determinations for the Metepec occupational phase in the site). There is one floating parameter (i.e. an event within the chronology about which we have absolutely a priori chronological information (Buck et al., 2001)), corresponding to the “Big Fire” dated to 550±25 AD by archaeomagnetism on lime plasters from two sites in Teotihuacan, Xalla and Teopanaczco (Manzanilla, 2003a,b; and Soler-Arechelade et al., 2006). The beginnings and endings for the four groups are not known. Data for samples and groups are shown in Table 1.

The first group of dates overlaps with the second group, which also overlaps with the third group. The fourth group is later than the third group and ends before the “Big Fire.”

There are eleven samples from Tlamimilolpa contexts (group 1), two of them (samples CAMS-132505 and CAMS-132511) are from the same sample and were treated as one sample by means of a pooled mean.

The second group corresponds to the transition between the Tlamimilolpa and Early Xolalpan (third group) occupational phases, because the samples grouped in it come from hearths associated to termination rituals of the late Tlamimilolpa phase (Manzanilla, 2003a, b, c, 2006). There are ten samples in this group, with three pairs of samples coming from the same sample and treated as pooled means (samples CAMS-132502 and CAMS-132508, CAMS-132503 and CAMS-132509, CAMS-132504 and CAMS-132510).

There are nine samples in the third group, Early Xolalpan, two of them (samples CAMS-132501 and CAMS-132507) coming from the same sample and treated as one sample by means of a pooled mean.

There are three samples in the fourth group, Late Xolalpan, one of them is sample Beta-180337 (2460±40 14C yr BP), which comes from a context presumably altered during the Batres excavation in 1884, this date is suspected to be an outlier.

Bayesian model B has the same conditions as model A but excludes two samples that resulted in having a 100% probability of being outliers in model A (sample Beta-180340 in group Early Xolalpan and sample Beta-180337 in group Late Xolalpan), This was performed in order to evaluate the effect of outliers on the calibrated date estimates.

Sensitivity analysis was performed by calibrating Bayesian scenario C, which excludes the outliers, and has the ending of Tlamimilolpa equal to the beginning of Early Xolalpan, with the transition overlapping both groups; and the ending of Early Xolalpan later than the beginning of Late Xolalpan.

Results and discussion

Individual calibrations: limitations derived from plateaus in the calibration curve

The individual calibrations for the samples result in calendar intervals spanning up to 440 yr (sample Beta-204325). This is mainly due to the area of the calibration curve in which the samples lie. There are three plateaus in the period of interest, ranging from 2500 14C yr BP to 1450 14C yr BP (Fig. 1), and 15 of the 33 samples touch one of these plateaus.

The first plateau is located between 2413 and 2429 14C yr BP. During this period of only 16 14C yr, the corresponding calendar interval spans 95 calibrated years (510–415 BC). There are two samples that lie in this plateau, samples Beta-180340 (2460±40 14C yr BP) and Beta-180337 (2460±40 14C yr BP), both have a good measurement precision with a standard deviation of ±40 14C yr, but as a consequence of the plateau the calibrated interval spans 346 yr, from 758 to 412 cal BC.

For the second plateau, located between 1839 and 1827 14C yr BP, a period of 12 14C yr corresponds to a calendar interval of 75 calibrated years, from 140 to 215 AD. There are eight samples covering this period (samples Beta-115496, Beta-118121, Beta-132603, Beta-132604, UGa-7506, CAMS-132505, CAMS-132511, and CAMS-132508). For example, sample Beta-115496 covers a period of 285 yr. The period between 1563 and 1590 14C yr BP is the third plateau. In this case a period of 27 14C yr corresponds to a 95 calendar year period, from 440 to 535 AD. There are five samples within this period (samples Beta-115487, Beta-129934, Beta-129935, Beta-204325, and Beta-204326). Samples Beta-129934 (1580±60 14C yr BP) and Beta-129935 (1590±70 14C yr BP) cover a calendar period of 260 and 290 yr, respectively, as a consequence of lying on the plateau.

Bayesian model A: reducing calibrated intervals

A comparison of the results obtained for individual and Bayesian model A calibrations is shown in Figure 2, and the posterior probability
density plots for some samples for each group and group boundaries are shown in Figures 3 and 4, respectively. It can be seen that with Bayesian model A the periods covered by the calibrated ages are considerably reduced, even down to a ca. 24% for sample Beta-204325 (1610±110 14C yr BP). An important feature of the calibrated interval with Bayesian model A for this sample is that it falls just before the third plateau, resulting in this significant reduction of the calibrated interval.

This is also the case for samples Beta-129934 (1580±60 14C yr BP) and Beta-129935 (1590±70 14C yr BP), which fall in a plateau of the calibration curve when individually calibrated. In Bayesian model A, however, the calibrated dates fall before the plateau resulting in an interval of 50 yr, 63% shorter than individual calibration.

For samples Beta-180340 and Beta-180337, both with a radiocarbon age of 2460±40 14C yr BP, the calendar intervals when calibrated with Bayesian model A do not correspond to the intervals when calibrated individually (i.e., they need a shift in the radiocarbon scale in order to be consistent with the rest of the samples: Christen, 1994). These samples were the only ones that resulted in a 100% a posteriori probability of being outliers.

Another important aspect of the results for Bayesian model A is that it is possible to identify the different groups or occupations. The first group, Tlamimilolpa, has a date of beginning between cal 90 AD and cal 240 AD. This is in accordance with the chronology for Teotihuacan proposed by Rattray (1991), which sets the beginning of the Tlamimilolpa period in 200 AD. Bayesian calibrated intervals for the samples in this group range from 110 AD to 290 AD. The ending for this group ranges from 220 AD to 315 AD.

For the group Tlamimilolpa/Early Xolalpan transition, the beginning is between 180 AD and 290 AD and the ending is between 260 AD and 350 AD, with calibrated intervals for the samples in this group ranging from 215 AD to 330 AD. This is earlier than expected because these samples are associated to hearths corresponding to termination rituals for the Tlamimilolpa phase. Burned lime-plasters coming from the floor beneath these hearths have been dated by archaeomagnetism at 350±25 AD (Hueda-Tanabe et al., 2004; and Soler-Arechalde et al., 2006).

For Early Xolalpan, the beginning is between 230 AD and 330 AD, and the ending is between 270 AD and cal 380 AD. The Bayesian calibrated intervals for the samples range from 230 AD to 365 AD. These results are
Figure 3. Probability distributions for some samples calibrated individually (black lines), with Bayesian model A (including outliers, gray lines), and with Bayesian model B (excluding outliers, gray areas). The ±1 sigma envelope for the IntCal-04 calibration curve is also shown with its y-axis on the right.
Figure 4. Posterior probability density plots for group boundaries of Bayesian model A (gray lines) and Bayesian model B (gray areas). The ±1 sigma envelope for the IntCal-04 calibration curve is also shown with its y-axis on the right.
again earlier than expected. In addition to the archaeomagnetic date for the termination rituals considered to mark the transition between Tlamilololpa and Early Xolalpan (350±25 AD), there is another archaeomagnetic date for burned lime plaster on the floor of a Xolalpan room from what appears to be an Early Xolalpan termination ritual, with a date of 425 AD (Hueda-Tanabe et al., 2004), making Bayesian model A results for this period at least 70 yr earlier than expected.

Finally, for Late Xolalpan the beginning ranges from 280 AD to 390 AD and the ending from 430 AD to 575 AD. Bayesian calibrated intervals for samples in this group range from 300 AD to 545 AD. As discussed above, the beginning of this period has an estimated age earlier than expected, as is also the case for the termination, which was expected to be ca. 550 AD, because the “Big Fire” marks the terminal event for this period.

These earlier results can be a consequence of the inclusion of the two outliers in these groups. This was explored by Bayesian model B and the results are discussed in the next section.

Comparison between Bayesian models A and B: effect of outliers

Bayesian models A and B can be compared in Figures 2, 3 and 4. Results for Bayesian model B are a bit later than for model A. The calibrated intervals for samples in model B are on average ca. 12% longer and a bit later than for model A.

Model B posterior probability distributions for samples in the Tlamilololpa group, although on average 23% longer, cover a calendar period very similar to distributions obtained with model A (Figs. 2 and 3). For samples in the Transition Tlamilololpa/Early Xolalpan group, Bayesian model B intervals are on average ca. 27% longer than model A intervals, and are slightly later (Fig. 3, samples Beta-132604 and Beta-204328), covering calendar intervals from 210 AD to 370 AD. Model B posterior probability distributions for samples in Early Xolalpan result in calendar intervals on average 18% longer than with model A, and all of them are later (Fig. 3, samples Beta-204325 and Beta-129935), covering calendar dates from 290 AD to 460 AD. For the two samples in the Late Xolalpan group, model B posterior probability distributions are 15% shorter than intervals in model A; from 430 AD to 565 AD.

Groups are more distinct in model B than in model A. Tlamilololpa group has a similar beginning in both models, between 50 and 240 AD; but the ending is slightly later, from 235 AD to 340 AD. For the Transition Tlamilololpa/Early Xolalpan group, the beginning is very similar as well, but the ending is later, from 290 AD to 410 AD. This is in accordance with the 350±25 AD archaeomagnetic date for burned lime plasters associated to termination rituals (Manzanilla, 2003b,c). Early Xolalpan begins between 260 AD and 370 AD, and ends between 345 AD and 480 AD, later than in model A. This is in accordance with archaeomagnetic dates previously mentioned, setting the beginning after 350±25 AD and the ending at 420 AD. Late Xolalpan group begins and ends later in model B than in model A, beginning between 400 AD and 550 AD and ending between 450 AD and 580 AD. This agrees with the archaeomagnetic
date for the Big Fire (550±25 AD). Group boundaries for model B are shown in Figure 5.

The differences between the Bayesian models A and B are more significant than expected. It has been reported that when there is a high a posteriori probability that a sample is an outlier, the inclusion of this sample should have a reduced impact on the calendar intervals estimated by the Bayesian model (Buck, 2004). In the results presented here, the inclusion of radiocarbon data of two outlier samples resulted in calibrated intervals earlier than those expected from archaeological inferences (model A). We consider this to be a consequence of these samples having radiocarbon dates too early for the site, 500 $^{14}$C yr earlier than the samples from the first occupational phase.

**Sensitivity analysis**

Bayesian model C was calibrated in order to evaluate the effect that differences in group boundaries have on the calibrated intervals. A comparison between models B and C is shown in Figure 6. The intervals covered by boundaries and samples (results not shown) for both models are similar, with intervals for model C on average 4.7% longer than for model B. The most significant difference is at the end of Tlamimilolpa, with the ending in model C 55 yr later than in model B.

The results from the sensitivity analysis confirm that the chronology for Teopancacazo, obtained through the Bayesian model calibration, is robust.

**Conclusions**

Calibration of radiocarbon dates with a Bayesian model was successfully performed for a set of 33 radiocarbon ages from an extensively excavated and studied site in the Mesoamerican center of Teotihuacan in Central Mexico. Results are consistent with the currently accepted chronology for the first two occupational phases, but suggest that the ending of the Xolalpan phase is around cal AD 550, 100 yr earlier than proposed by Rattray (1991).

There are interesting correspondences with the archaeological data, particularly from primary contexts excavated at Teopancacazo. The end of the Tlamimilolpa period at cal AD 350 suggests that something very important happened at Teotihuacan around that time, perhaps related to the demise of the Feathered Serpent group. That demise signaled a new construction phase in the city (the so-called “urban renewal” by Millon, 1973), and was marked by different types of termination rituals at Teopancacazo (Manzanilla, 2002, 2003c) such as massive crushing of pottery and instruments and the decapitation of...
male individuals (Manzanilla, 2006). Further, results obtained for the ending of Early Xolalpan agree with the archaeomagnetic date reported by Hueda-Tanabe et al. (2004) that dates the termination ritual by 420 AD. With respect to the end of the Xolalpan phase around AD 550, we have the great fire of the Teotihuacan core, perhaps an internal revolt, with archaeomagnetic dates in Xalla and Teopancacazo (Soler-Arechalde et al., 2006) around that time. We also have the shattering of the cult sculptures in the main temples and precincts along the Street of the Dead (Manzanilla, 2003b,c). Finally, around AD 600 there are groups of people in the Teotihuacan valley, perhaps coming from the Bajío Region in Western Mexico (the so-called “Coyotlatelco”), living inside the tunnels behind the Pyramid of the Sun and looting the core of the Classic City (Manzanilla et al., 1996). Therefore, it is probably sound to propose that the Metepec phase abandonment of large sectors, and reoccupation by the Coyotlatlelco ended around AD 600 with the total collapse of the metropolis, the abandonment of large sectors, and reoccupation by the Coyotlatlelco groups. For these reasons it can be considered that the chronology obtained for Teopancacazo is a first step in the generation of a high-resolution chronology for the city of Teotihuacan in order to help elucidate the current debate about its abandonment.

The use of Bayesian model B reduced the uncertainties in the calibrated intervals between 70 and 20% and permits to distinguish the different occupations. Bayesian statistics, however, has to be applied with caution. Reliability of the results will depend on the a priori information and the quality of the radiocarbon ages. Including radiocarbon data from outlier samples can have significant impacts. In this work, the inclusion of two samples (out of 33) from two altered contexts, 500 14C yr earlier than the samples from the first occupation, resulted in calendar intervals earlier than expected. Excluding these samples from the Bayesian model, after confirming they were outliers, provides good correlation with intervals defined by archaeomagnetic dates obtained for the same site.

Acknowledgments

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