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Regional response to drought during the formation and decline of Preclassic Maya societies

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ABSTRACT

The earliest complex societies and a distinctive set of pan-regional social, political, and economic institutions appeared in the southern Maya lowlands during the Preclassic period (ca. 1200/1100 cal BCE–cal 300 CE). The timing of these cultural changes was variably influenced by local developments, interaction with other regions of Mesoamerica, and climate change. We present a high-resolution radiocarbon chronology for the growth of the early polity of Cahal Pech, Belize, one of the first permanent settlements in the southern Maya lowlands. We compare our results to a database containing over 1190 radiocarbon dates from cultural contexts reported from five major regions of the southern lowlands to interpret the expansion and decline of emerging complex social groups during the Preclassic. Comparisons to paleoclimate proxy datasets suggest that fluctuating climate regimes may have promoted alternating integration and fragmentation of early hierarchically organized societies. Stable climatic conditions during the Middle Preclassic (1000/900-300 cal BCE) fostered the centralization of populations and the formation of large regional polities across the southern lowlands. An extended drought at the end of the Late Preclassic (cal 150–300 CE) likely contributed to the decline of some major polities in the central Petén, but smaller sites located in productive environments were more resilient and persisted in to the Classic period. This research provides a framework for understanding the complex social and environmental factors that influenced localized adaptations to climate change and the episodic growth and decline of early complex societies in prehistory.

1. Introduction

The questions of when, why, and how hierarchical societies emerge, grow, and disintegrate, and why some were more resilient than others have been topics of archaeological research for decades (Kintigh et al., 2014). The development of the earliest complex prehistoric societies was a long-term and dynamic process driven by various cultural and environmental factors. Complex societies, characterized by institutionalized social and economic inequality, developed in the context of population aggregation along with new forms of management and production of subsistence resources, control of labor, and control of economically important goods by leaders. These activities resulted in the formation of multi-level economic, social, and political networks between groups, allowing paramount centers to become central nodes within increasingly interconnected socio-political systems (Cowgill, 2012; Earle, 1987, 2002; Flannery, 1999; Turchin, 2003; Willey, 1991). The resilience of early complex societies was challenged by endogenous and exogenous factors, frequently resulting in the fragmentation of paramount polities and sometimes the development of completely new social systems (Carneiro, 1970; Wright, 1994; Steward, 1955:51). This type of socio-political cycling has been documented in multiple regions of the world in prehistoric and historic contexts including the Near East (Wright, 1994; Wright and Johnson, 1975), Europe (Shennan et al., 2013), Mesoamerica (Marcus, 1993, 1998, 2012; Smith, 1992), eastern North America (Anderson, 1996), and the Southwest US (Bocinsky et al., 2016).

Increasing emphasis has been placed on examining the role of

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coupled socio-natural systems in the historical dynamics related to the emergence and disintegration of complex societies in the past (de Menocal, 2001; Dillehay and Kolata, 2004; Kennett and Marwan, 2015; Rosen and Rivera-Collazo, 2012; Gavrilets et al., 2010). Archaeologists working in the southern Maya lowlands of Mexico, Guatemala, Belize, and Honduras have drawn from several sources to build models that define cycles of socio-political organizational change during the later Classic and Postclassic (~250–1500 CE) periods. Most notably, Marcus (1993, 1998) developed the "dynamic model" based primarily on glyphic texts recording dynastic histories, political alliances, and conflicts between divine kings from several lowland polities (see also Martin and Grube, 2008; Schele and Freidel, 1990). Under the dynamic model, Classic Maya prehistory is characterized by a series of recurring peaks and valleys between cal 250–900/1000 CE, which correspond to the centralization and decentralization of political systems, as well as to broad-scale regional variability in social integration and complexity. During two prominent peaks in the cycle (400–550 CE and 600–800 CE) elite dynasties located at paramount centers (e.g., Tikal, Calakmul, Caracol, Naranjo) were territorially extensive with multi-tiered settlement hierarchies. The expansion of these sites is coincident with a period of high precipitation recorded in regional paleoclimate records (Douglas et al., 2016b; Kennett et al., 2012; Hodell et al., 2005; Medina-Elizalde et al., 2010), which favored stable environmental conditions and fostered agricultural production, population expansion, and aggregation. Valleys in the cycle often correspond with periods of climatic stress. During the Terminal Classic period, paleoclimate data document numerous severe multi-decadal droughts occurring between cal 820–1100 CE, which likely influenced several waves of societal collapse, first in the southern lowlands and then in the northern lowlands of the Yucatán Peninsula (Akers et al., 2016; Curtis et al., 1996; Douglas et al., 2015; Haug et al., 2003; Hodell et al., 1995, 2005; Hoggarth et al., 2016; Kennett et al., 2012; Medina-Elizalde et al., 2010).

Significant cycles of social and political development also occurred earlier in the Maya lowlands during the Preclassic period (~1200/1000 cal BCE-cal 350 CE; Table 1). This period represents one of the most critical transitions in Maya prehistory, when the development of sedentary village life, increased reliance on maize agriculture, and the adoption of ceramic technology first appeared. These developments occurred several centuries earlier in other regions of Mesoamerica, and the details of the processes influencing the later adoption of sedentary farming lifestyles in different regions of the Maya lowlands remain unresolved (Clark and Cheetham, 2002; Lohse, 2010). By the Late Preclassic, however, archaeological data indicates that Maya society had become complex and hierarchically organized, with centralized polities serving as focal points for civic and ritual activity (Chase and Chase, 2012:259; Estrada-Belli, 2011; Schele and Freidel, 1990; Hansen et al., 2002; Inomata et al., 2017; Stanton, 2012; Stanton and Ardren, 2005). The appearance of monumental architecture and development of long-distance exchange networks during this time also signal the formation of an elite class that centralized wealth and power in the region (Doyle, 2017; Estrada-Belli, 2011). Paleoclimate research has indicated that the expansion and contraction of Preclassic Maya society was influenced in part by environmental factors. Particular attention has been paid to an extended period of drought at the end of the Late Preclassic (~cal 100–300 CE), which has been linked to population decline and abandonment of some major lowland centers, as well as a hiatus in construction activity in some parts of the southern lowlands (Haug et al., 2003; Dunning et al., 2014; Medina-Elizalde et al., 2016; Webster, 2002).

Table 1
Lowland Maya chronological periods.

Time Period	Calibrated Date Span
Colonial	1519–1821 CE
Postclassic	900/1000–1500 CE
Terminal Classic	800–900/1000 CE
Late Classic	600–800 CE
Early Classic	250/300–600 CE
Late Preclassic	300 BCE–250/300 CE
Middle Preclassic	1000–300 BCE
Early Preclassic	1200–1000 BCE

In this paper, we examine the cultural and climatic context for the development of Cahal Pech, an important Preclassic regional center located in the Belize Valley of modern-day Belize (Fig. 1). Cahal Pech provides a case study for understanding the origins and development of prehistoric lowland Maya society because it has a long occupational history beginning first in the Early Preclassic (~1200-1000 cal BCE) and ending during the Terminal Classic period (cal 850–900/1000 CE). We developed a high-resolution Bayesian radiocarbon chronology to understand the timing and tempo of development within the Cahal Pech civic-ceremonial site core, and for the residential settlement surrounding the center. We then compare the Cahal Pech chronology to a larger dataset of published radiocarbon dated cultural contexts ($n = 1196$) within the Belize Valley and other major regions of the southern Maya lowlands. Bayesian radiocarbon chronological models and summed probability distributions were created for five core regions of the lowlands in order to clarify the timing of localized Early through Late Preclassic social, political, and economic developments in relation to regional paleoclimate records. The results of this study serve to clarify long-term trends in socio-political dynamics at the local and regional levels in the southern Maya lowlands, and help to interpret the role of climate change as one possible mechanism for cultural evolution during the Preclassic. Constraining the timing of cultural change in relation to past climate change has implications for understanding long-term global social and environmental developments in both the past and the future.

2. Background

2.1. Preclassic climate regimes

Archaeological and paleoclimate studies have highlighted variability in human responses to environmental change as a potential factor in the episodic expansion and breakdown of prehistoric and modern societies (Axtell et al., 2002; Brenner et al., 2002; Haug et al., 2003; Dillehay and Kolata, 2004; Douglas et al., 2016a,b; Hoggarth et al., 2016; Iannone, 2014; Kennett et al., 2012; Kennett and Marwan, 2015; Ridley et al., 2015). In the Maya region, the first comprehensive paleoclimate proxy studies from lake sediment records in northern Yucatán showed temporal variations in sedimentation rates and evaporation and precipitation records based on oxygen isotopes ($\delta^{18}O$) of ostracods and gastropods, which correspond to multi-decadal dry episodes from the Preclassic through Postclassic periods (Hodell et al., 1995, 2005; Curtis et al., 1996; Rosenmeier et al., 2002). These drought events correlate closely with broader climate histories from the circum-Caribbean recorded in the Cariaco Basin sediment Ti record, especially during the Terminal Classic when the most severe and protracted droughts likely influenced the Classic Maya "collapse" (Haug et al., 2003).

More recently, high-resolution speleothem records from both the northern and southern lowlands have supported the hypothesis that multi-decadal droughts played a role in several waves of socio-political disintegration between cal 850–1100 CE (Akers et al.,

Fig. 1. Locations of major Preclassic period sites and paleoclimate records discussed throughout the text. The primary regions examined in this paper include 1) the Belize Valley and Vaca Plateau, 2) Northern Belize, 3) the Petén and Southern Belize region, 4) the Pasión region, and 5) the Southeastern Periphery. Inset map shows the location of Cahal Pech in relation to other major Preclassic Belize Valley sites.

2016; Kennett et al., 2012; Medina-Elizalde et al., 2010). The first wave of collapse occurred in the southern lowlands, and resulted in the decentralization of regional political and economic systems, abandonment and depopulation of large urban centers, and the disappearance of traditions associated with divine rulership (Aimers, 2007; Demarest et al., 2004; Ebert et al., 2014; Webster, 2002). The second wave of collapse centered on the major northern lowland polity of Chichén Itzá between cal 1000–1100 CE during the most acute drought recorded in the regional paleoclimate records (Hoggarth et al., 2016; Kennett et al., 2012). Written records and paleoclimate evidence from historic datasets similarly demonstrate a close correspondence between socio-political reorganization and climate variability in the northern lowlands of Yucatán during the Colonial period, especially in the context of severe drought that impacted subsistence production and local demographics (Bricker and Hill, 2009; Endfield, 2007; García-Acosta et al., 2003; Hoggarth et al., 2017).

While many paleoclimate records from the northern and southern lowlands span the duration of the Preclassic period, less research has been devoted to understanding climate cycles during

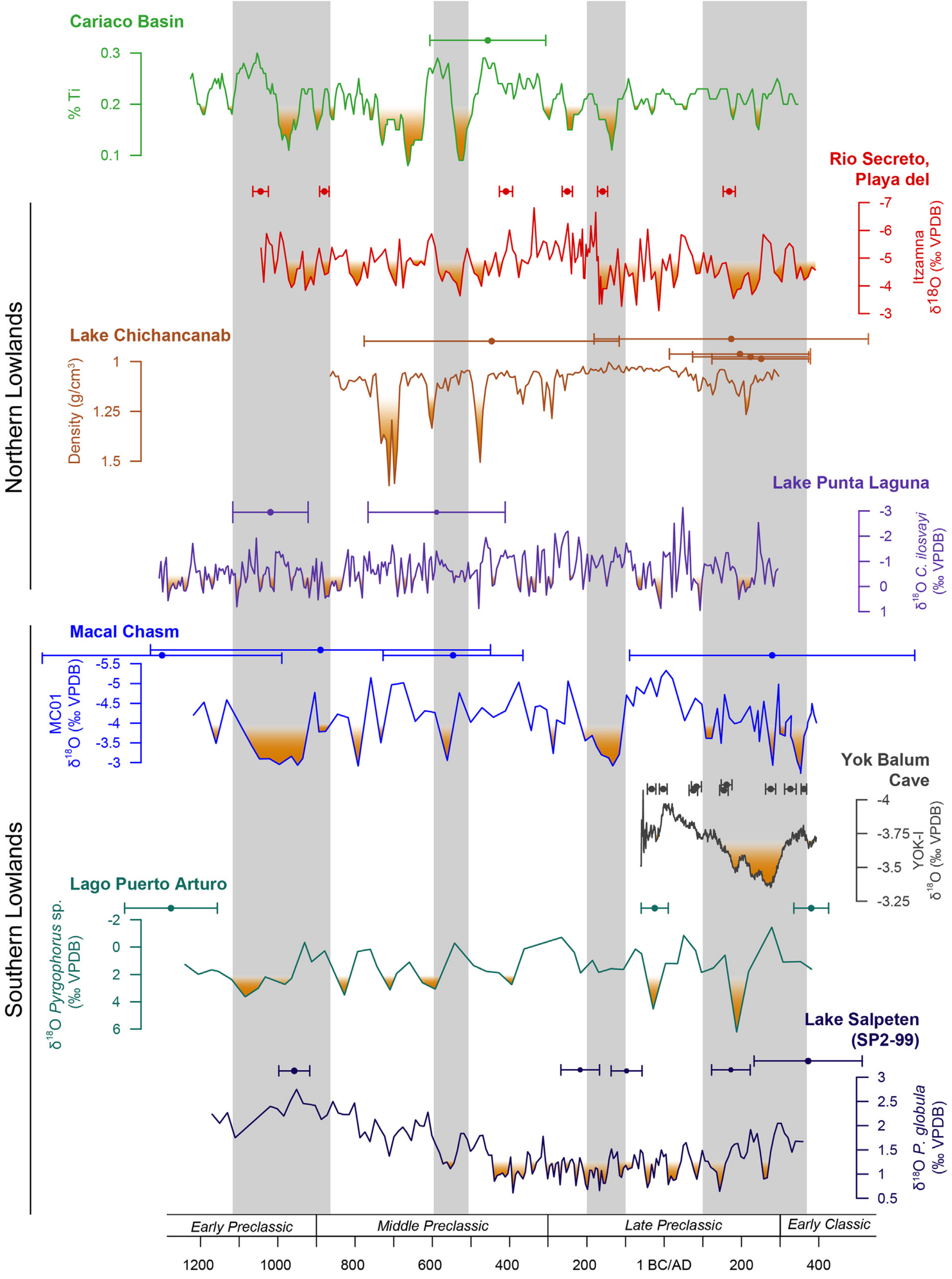

Fig. 2. Preclassic paleoclimate records from the circum-Caribbean region and the northern and southern Maya lowlands, including: A) Cariaco Basin Ti record (Haug et al., 2003), B) Río Secreto "Itzamna" $\delta^{18}O$ speleothem record (Medina-Elizalde et al., 2016), C) Lake Chichancanab sediment density record (Hodell et al., 2005), D) Lake Punta Laguna ostracod (*Cytheridella ilosvayi*) $\delta^{18}O$ record (Curtis et al., 1996), E) Macal Chasm (MC01) $\delta^{18}O$ speleothem record (Akers et al., 2016), F) Yok Balum Cave (YOK-I) $\delta^{18}O$ speleothem record (Kennett et al., 2012), G) Lago Puerto Arturo gastropod (*Pyrgophorus* sp.) $\delta^{18}O$ record (Wahl et al., Zone (Akers et al., 2016) and H) Lake Salpetén gastropod (*P. globula*) $\delta^{18}O$ record (Rosenmeier et al., 2002). Major multi-century dry events from the Macal Chasm speleothem record are highlighted in gray.

this time. Two recently published speleothem records from these regions are beginning to clarify the timing of short-term pulses and long-term trends in Preclassic climate regimes (Fig. 2). The Itzamna speleothem record from Río Secreto, Playa del Carmen in northern Yucatán provides the highest resolution paleoclimate record for the Preclassic Maya lowlands (Medina-Elizalde et al., 2016). The record is dated with six uranium-thorium series measurements resulting in estimates for relative amounts of rainfall every 8–10 years. Oxygen isotope ($\delta^{18}O$) measurements ($n = 2545$) of incremental stalagmite growth show alternating wet and dry periods from approximately 1040 cal BCE through cal 400 CE. Several droughts, characterized by a reduction in precipitation levels between 35% and 50% relative to average amounts, punctuate the record approximately every century during the Middle Preclassic period. A gradual negative shift in average $\delta^{18}O$ values occurs in the Itzamna record around 520 cal BCE, marking the beginning of a humid period during the Middle Preclassic, when estimated precipitation levels increased by over 20% across northern Yucatán (Medina-Elizalde et al., 2016). This shift to wetter conditions is mirrored in $\delta^{18}O$ values from lake sediment core records from other parts of the northern lowlands (Punta Laguna, Hodell et al., 1995; Curtis et al., 1996; Lake Chichancanab, Hodell et al., 2005), as well as in the central Petén (Lake Salpetén, Douglas et al., 2016b; Rosenmeier et al., 2002; Lago Puerto Arturo, Wahl et al., 2013, 2014), indicating that humid conditions were present in the greater Maya lowland region by the end of the Middle Preclassic.

The site of Macal Chasm, located 22 km southeast of the Belize Valley in the Vaca Plateau of west-central Belize, has produced the closest paleoclimate proxy record to the site of Cahal Pech. A total of 660 $\delta^{18}O$ and $\delta^{13}C$ measurements were sampled from the MC01 speleothem at a resolution of 24–15 years for the Preclassic section of the record (Akers et al., 2016; Webster et al., 2007). The record is anchored with 21 uranium-thorium dates, with average measurement errors between 250 and 380 years. The appearance of major dry events begin after 2000 cal BCE, and coincide with more intense El Niño phases and a southern shift in the Intertropical Convergence. While short-term shifts in wet and dry conditions punctuate the record, multi-decadal major dry intervals in the Macal Chasm record are associated with sustained values of δ18O and δ13C significantly higher (greater than 1‰ and 3‰, respectively) than bracketing periods. Major dry events are recorded for the periods between 1110 and 890 cal BCE, 590-550 cal BCE, 190-110 cal BCE, and cal 250–330 CE. While, some of these dry events span over two centuries, they generally consist of shorter-term droughts of varying intensities with brief wet intervals (Akers et al., 2016). Though the timing and magnitude of climatic fluctuations varied across different regions of the Maya lowlands (see Aimers and Hodell, 2011), the comparison of the Itzamna and Macal Chasm speleothem records with climate proxies from other parts of the Maya area (southern and northern lowlands) show clear and congruent long-term climate trends within the limits of dating errors of individual records.

Increasing emphasis has especially been placed on a prolonged period of climatic volatility at the end of the Late Preclassic as a catalyst for social and political reorganization in the southern lowlands (Dunning et al., 2014; Haug et al., 2003; Kennett et al., 2012; Medina-Elizalde et al., 2016; Wahl et al., 2014). The onset of dryer climatic conditions during the Late Preclassic is characterized by several droughts occurring over the course of approximately two centuries (~200-1 cal BCE), with precipitation reduced by up to 65–75% for this period generally. The most acute Preclassic droughts occurred after cal 160 CE (Kennett et al., 2012; Dunning et al., 2014; Medina-Elizalde et al., 2016). In the northern lowlands, the Itzamna speleothem record documents two successive multi-decadal droughts centered at ~ cal 190 and 230 CE, lasting approximately 31 and 22 years, respectively (Medina-Elizalde et al., 2016). Severe precipitation reduction in the northern lowlands is also recorded by increased levels of gypsum deposition in Lake Chichancanab sediments (Hodell et al., 2005) and by positive shifts in average $\delta^{18}O$ values in the Lake Punta Laguna record between cal 125–210 CE (Curtis et al., 1996; Hodell et al., 1995). Similar trends in climatic fluctuations also occurred in the southern lowlands at the end of the Late Preclassic. The sub-annually resolved YOK-I speleothem record, from Yok Balum Cave in southern Belize, shows two major droughts during the Late Preclassic, the second of which was the most extreme and lasted over a century (cal 200–300 CE; Kennett et al., 2012). Lake sediment core records from Lago Puerto Arturo in the Mirador Basin (Wahl et al., 2014) and Lago Salpetén (Douglas et al., 2016b) also indicate reduction in precipitation and increased levels of evaporation over several centuries at the end of the Late Preclassic period. These extreme dry conditions temporally parallel the cessation in the construction of monumental architecture and depopulation of some major centers (e.g., Nakbe and El Mirador) in the Petén (Beach et al., 2015; Dunning et al., 2012; Wahl et al., 2007; Webster, 2002).

2.2. Preclassic period archaeological records

The establishment and expansion of Preclassic Maya society occurred in several pulses, each characterized by distinctive economic innovations and socio-political changes, all within the context of fluctuating climatic regimes. Radiocarbon dates from sites located on the southeastern periphery of the Maya lowlands in Honduras document the presence of small localized hunting and foraging populations in the area between ~8000 and 4000 cal BCE (e.g., El Gigante Rockshelter; Kennett et al., 2017; Scheffler et al., 2012). In the southern lowlands, Archaic period occupation is not well defined until approximately ~1500 cal BCE, when directly dated deposits containing chipped stone tools, faunal remains, and maize pollen document the presence of pre-ceramic populations in northern and western Belize (Clark and Cheetham, 2002; Iceland, 1997, 2005; Lohse, 2010; Rosenswig, 2015; Stemp et al., 2016). The transition to sedentary village life first occurred in these regions at the end of the Early Preclassic (1200/1000 cal BCE), when people began to aggregate in small, relatively egalitarian villages within economically autonomous households (Awe, 1992; Clark and Cheetham, 2002; Estrada-Belli, 2011; Inomata et al., 2015, 2017; Lohse, 2010). Accompanying the transition to sedentism was an increasing commitment to maize agriculture, the adoption of ceramic technology, long-distance interaction with other groups in Mesoamerica, and early public architecture programs (Chase and Chase, 2012).

Distinctive and diverse pre-Mamon ceramic complexes associated with early village communities have been documented in four primary core regions of the southern lowlands (Fig. S1): west-central Belize in the Belize Valley (Cunil ceramic complex, Sullivan and Awe, 2013; Kanocha ceramic complex, Brown and Garber, 2005; Garber et al., 2004), Northern Belize (Swasey ceramic complex; Kosakowsky, 1987), central Petén (Eb ceramic complex, Culbert, 1977; Laporte and Fialko, 1993; Laporte and Valdés, 1993; K'awil ceramic complex, Callaghan and Nievens de Estrada, 2016), and the Pasión area (Real ceramic complex, Inomata et al., 2013, 2015, 2017; Xe ceramic complex; Adams, 1971). Many of these early ceramics bear symbols connecting them with contemporaneous iconographic traditions developing elsewhere in Mesoamerica along the Gulf Coast and Oaxaca (Cheetham, 1998; Callaghan and Nievens de Estrada, 2016; Garber and Awe, 2009; Hammond, 2006; Inomata et al., 2013; Sullivan and Awe, 2013; Valdez, 1988). A similar pattern of early settlement, ceramic use, and construction of public architecture by the end of the Early

Preclassic and beginning of the Middle Preclassic may also be present in northeastern Yucatán at the sites of Komchen, Yaxuná, and Xocnaceh in northern Yucatán, represented by the early Nabanche (Ceballos Gallareta and Robles Castellanos, 2012) and Ek and ceramic complexes (Ringle, 1991; Stanton, 2012), though the chronologies for these developments remain debated.

During the Middle Preclassic period, population expansion and economic growth across the much of the southern lowlands were accompanied by the adoption of a more standardized Mamon ceramic tradition (monochrome, red-slipped pottery; Willey et al., 1967) and intensified construction programs of public architecture (Doyle, 2017; Estrada-Belli, 2011; Hansen, 1998; Inomata et al., 2017). Taken together, these developments signal the centralization of economic power and the emergence of higher status individuals within local communities (Chase and Chase, 2012; Clark and Hansen, 2001). Higher-status individuals often lived in larger households, and placed burials beneath house floors to promote continuity of settlement at the site and reinforce ties to land and access to resources (McAnany, 1995). Lowland Maya society experienced a fluorescence during the end of the Middle Preclassic and into the Late Preclassic, when large civic-ceremonial centers and archaeological evidence for institutionalized elite rulership first appear (Awe et al., 2009; Estrada-Belli, 2011:44–48; Freidel and Schele, 1988; Hammond, 1980:189; Hansen, 2005). These cultural changes were relatively abrupt, and are best represented at the sites of El Mirador and Nakbe, where an elite ruling class was able to mobilize labor for massive construction projects and tap into long-distance exchange networks to acquire exotic prestige items to reinforce their authority (Hansen, 1998, 2001; Hansen and Guenter, 2005). At Nakbe, monumental architecture including ball courts, an E-Group architectural assemblage, and monumental stucco masks on public buildings first appeared around 600 cal BCE (Hansen, 1998). After 400 cal BCE, the site of Mirador emerged as the largest and most complex Preclassic polity in the Maya lowlands, extending over 3 km^2 with several massive temple complexes (Hansen et al., 2008; Sprajc, 2002). By 300 cal BCE, the appearance of hieroglyphic texts carved stone monuments with the "*ajaw*" (i.e., divine king) glyph demonstrate the existence of institutionalized rulership at this site and likely elsewhere in the region (Saturno et al., 2006). These texts also linked Maya rulers with the cosmos to bolster their political competitiveness (Chase and Chase, 2012). Well-documented elite tombs placed within public architectural complexes containing a wealth of local and exotic grave goods appear at Tikal and Holmul sites by the 100 cal CE, providing evidence for institutionalized kingship (Estrada-Belli, 2011).

Settlement data document the abandonment of the large polities of El Mirador and Nakbe, as well as other sites in the Petén, from 150–250 CE at the end of the Late Preclassic period (Beach et al., 2015; Dunning et al., 2012; Hansen et al., 2008). Several studies have suggested that these paramount centers were depopulated in the face of deteriorating climatic conditions during what has been referred to as a "mega-drought" (Akers et al., 2016; Haug et al., 2003; Hodell et al., 2005; Kennett et al., 2012; Medina-Elizalde et al., 2016). Responses to severe drought, however, appear variable across the southern lowlands. Persistence in site occupation has been documented in Northern Belize, with populations contracting around centralized locations that later developed into large Classic period polities (Rosenswig and Kennett, 2008). Some sites in the Belize Valley and Petén show shifts in monumental traditions, including a decline in the construction of eastern triadic groups (e.g., Cahal Pech, Awe, 2008; Awe and Helmke, 2005; Ebert et al., 2016a), and in some cases reorganization of the monumental site centers (e.g., Tikal, Martin, 2003; Schele and Freidel, 1990). Glyphic texts on carved stone monuments that placed emphasis of dynastic rulership also appeared at the end of the Late Preclassic, representing a new form of political competitiveness between polities (Chase and Chase, 2012).

2.3. The Belize valley Preclassic and Cahal Pech

The site of Cahal Pech is located in the Belize Valley of the west-central portion of the modern country of Belize. Fragments of eight plain stelae and four altars within the monumental epicenter and lavish royal burials within large monumental architecture indicate a civic-ceremonial function for the site during the Classic period (Awe and Zender, 2016). A program of stratigraphic excavations conducted in the ceremonial center within Plaza B and at Structure (Str.) B4, on the south side of the plaza, by the Belize Valley Archaeological Reconnaissance (BVAR) Project has been ongoing since 1988 and is aimed at understanding the foundation and early growth of Cahal Pech into a major civic-ceremonial center during the Preclassic (Fig. 3; Awe, 1992; Awe and Helmke, 2005; Healy et al., 2004a; Horn, 2015; Peniche May 2014, 2016).

Str. B4 is a 5.5 m high temple located at the southeastern corner of Plaza B, and has produced the longest dated construction sequence at Cahal Pech. A series of excavations conducted by the BVAR Project documented at least 13 discrete construction episodes (Figs. S2 and S3; Awe, 1992; Garber and Awe, 2009; Healy and Awe, 1995; Healy et al., 2004a; Ishihara-Brito and Awe, 2013). The uppermost strata of the building are composed of Classic period materials, which also contain intrusive Terminal Classic burials (Awe, 1992, 2013). Materials located below Floor 3 (Str. B4/10th) are associated with Early through Late Preclassic occupation. Plaza B is the largest open courtyard in the Cahal Pech civic ceremonial core, measuring approximately 50 m by 60 m. Large scale horizontal exposures and test pits (Awe, 1992; Garber et al., 2010; Healy et al., 2004a; Horn, 2015; Peniche May 2016) have identified contexts representing the earliest village settlement and the earliest ceramics at the site during the Cunil ceramic phase (~1200/1100-900 cal BCE) within Plaza B and Str. B4. While some scholars have suggests that the Cunil and other pre-Mamon ceramic phases first begin around 1000 cal BCE (Inomata, 2017; Inomata et al., 2017; Lohse, 2010), excavations and radiocarbon dating at Cahal Pech have documented Cunil ceramic materials present within primary contexts in the lower most levels at Str. B4 and Plaza B dating as early as 1200/1100 cal BCE (Sullivan and Awe, 2013). Associated architecture within these early contexts consists of simple wattle and daub structures sometimes placed directly on top on modified bedrock that served as dwellings or out-buildings (Awe, 1992; Horn, 2015; Garber et al., 2004; Peniche May 2016). The recovery of Cunil phase ceramics and domestic refuse at the lowermost levels of excavations in the Zopilote and Zubin settlement groups, south of the Cahal Pech core, indicates that similar small villages may have contemporaneously existed in these locations (Ebert and Fox, 2016; Iannone, 1996). Archaeological and radiocarbon evidence and direct dates also document the founding of settlements by at least 1000 cal BCE, if not a century earlier, at the nearby Belize Valley sites of Blackman Eddy (Garber et al., 2004), Xunantunich (Brown et al., 2013), and Actuncan (LeCount et al., 2002, 2017). Initial occupation at these sites is associated with the appearance of the Cunil/Kanocha ceramic materials that are usually found at the bottom of deeply stratified Classic period sequences (Awe, 1992; Sullivan and Awe, 2013).

At the beginning of the Middle Preclassic (Early Facet Kanluk ceramic phase; 900–650 BCE) architecture within the Cahal Pech site center increased in size to include large raised platforms constructed from high-quality cut limestone (Awe, 1992; Healy et al., 2004a; Horn, 2015; Peniche May 2016). During this time the inhabitants of Blackman Eddy (Brown, 2003; Brown and Garber, 2005, 2008; Garber et al., 2004) and Actuncan (LeCount et al.,

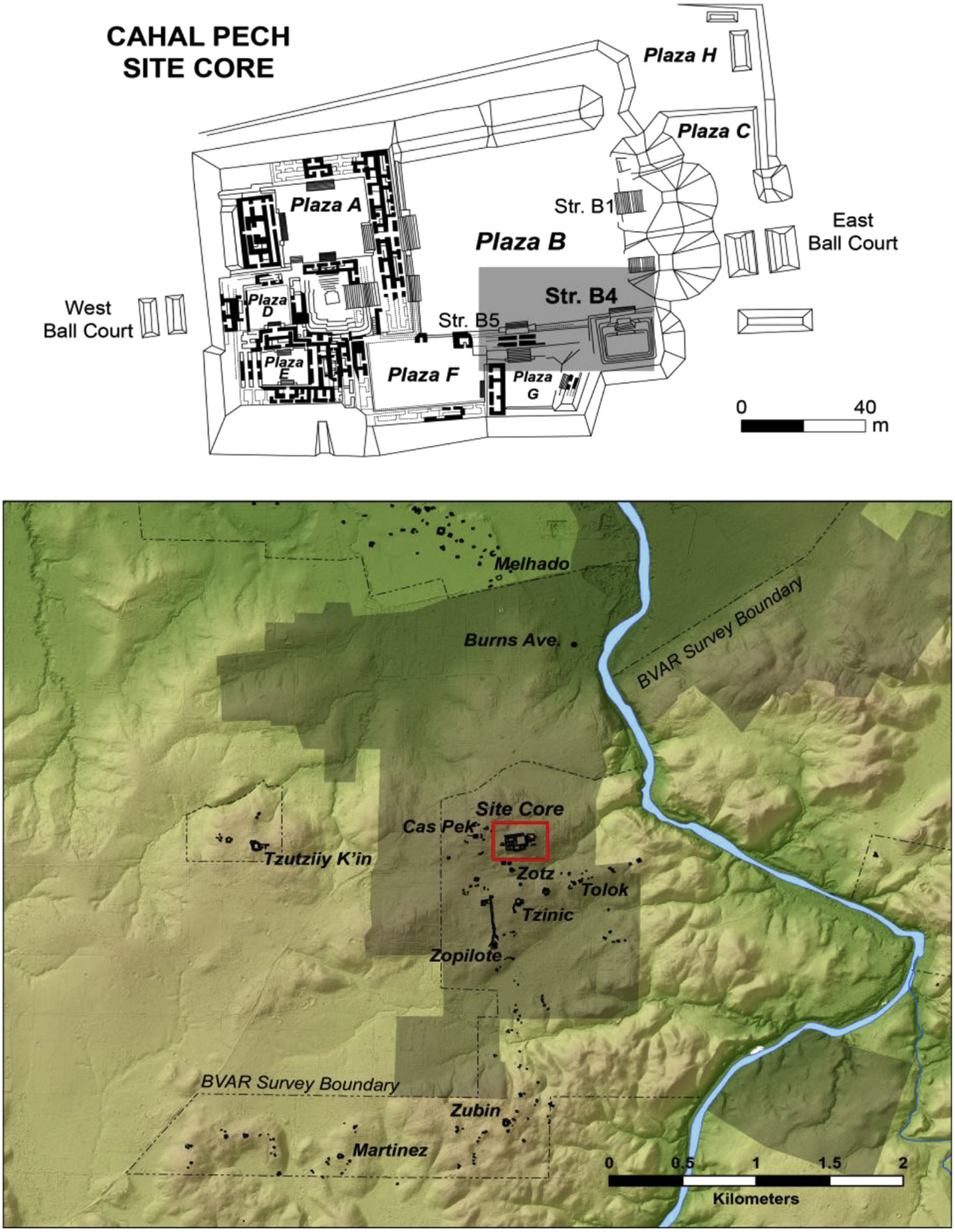

Fig. 3. Upper map shows location of Cahal Pech site core with approximate locations of excavations in Plaza B and Structure B4 shaded in gray. The lower map show the location of the site core in relation to outlying residential settlement with the extent of the modern town of San Ignacio shaded.

2017) also constructed plastered platforms that may have been used for public functions, including communal rituals. At Xunantunich, a large pyramidal structure was constructed in Group E, and evidence exists for the differential distribution of specialized craft production at several locations around the site (Brown et al., 2013, 2016). While there is evidence for differential access to resources by some households during the Middle Preclassic, the clearest evidence for institutionalized social differentiation appears in the Late Preclassic (300 cal BCE-cal 300 CE) at Cahal Pech, when the presence of monumental architecture and the first elaborate burials indicate it was the seat of power for a small regional polity (Awe, 2013; Awe and Zender, 2016; Novotny, 2015). A carved monument discovered in a tomb in the southern perimeter of the site core at the Zopilote Group has been stylistically dated to the early

Table 2
Radiocarbon dates for Structure B4 and Plaza B South Excavations in the Cahal Pech monumental site core considered in this study.

Sequence	Lab #	Provenience	Material	Conventional ^{14}C age (BP)	Unmolded 2σ cal range (BCE/ CE)	Associated Ceramics	Reference
Structure B4							
	UCIAMS-115021	EU10, L4. Above Fl. 4	Charcoal	2225 ± 15	375–205 BCE	EF/LF Xakal	
	UCIAMS-115022	EU10 L6. Surface Fl. 6A	Charcoal	2705 ± 15	900–815 BCE	EF Xakal	
	Beta-40863[a]	EU5, Fl. 7	Charcoal	2470 ± 90	795–400 BCE	LF Kanluk	Awe 1992
	UCIAMS-115023	EU10, L7. Surface Fl. 7	Charcoal	2585 ± 15	805–775 BCE	EF Kanluk	
	UCIAMS-115024	EU10, L8. Surface of Fl. 8	Charcoal	2735 ± 20	920–825 BCE	EF Kanluk	
	UCIAMS-111159	EU10, L8. In Fl. 8	Charcoal	2505 ± 15	775–545 BCE	EF Kanluk	
	Beta-77206[a,b]	EU5, Fl. 8	Charcoal	1950 ± 200	405 BCE–540 CE	EF Kanluk	Healy and Awe 1995
	Beta-40864 [a]	EU5, Fl. 9	Charcoal	2720 ± 60	1000–795 BCE	EF Kanluk	Awe 1992
	UCIAMS-111160	EU10, L10. Fl. 10	Charcoal	2220 ± 15	365–205 BCE	Cunil	
	Beta-40865 [a]	EU5, Fl. 10C	Charcoal	2740 ± 70	1055–795 BCE	Cunil	Awe 1992
	Beta-77205	EU5, Fl. 10A	Charcoal	2800 ± 50	1110–830 BCE	Cunil	Healy and Awe 1995
	Beta-77204 [a]	EU5, Fl. 11	Charcoal	2710 ± 120	1215–540 BCE	Cunil	Healy and Awe 1995
	Beta-56765 [a]	EU5, Fl. 11	Charcoal	2730 ± 140	1285–510 BCE	Cunil	Awe 1992
	UCIAMS-111158	EU8, L12/13. Fl. 13	Charcoal	2830 ± 15	1030–920 BCE	Cunil	
	UCIAMS-111162	EU10, L21. Fl. 13	Charcoal	2845 ± 20	1075–920 BCE	Cunil	
	UCIAMS-111161	EU10, L14. Southern posthole	Charcoal	2435 ± 20	745–405 BCE	Cunil	
	Beta-77207	EU5, Below Fl. 13, on bedrock	Charcoal	2930 ± 50	1280–980 BCE	Cunil	Healy and Awe 1995
Plaza B South Excavations							
	UCIAMS-169810	Lot PL-B-224, Below Fl. 4	Charcoal	180 ± 15	1665–1950 CE	Xakal/Mount Hope	
	UCIAMS-169811	Lot PL-B-263, Below Fl. 5	Charcoal	205 ± 20	1650–1950 CE	EF/LF Xakal	
	UCIAMS-169812	Lot PL-B-228, Below Fl. 6	Charcoal	155 ± 15	1665–1945 CE	EF/LF Xakal	
	UCIAMS-169813	Lot PL-B-24, Below Fl. 8	Charcoal	2035 ± 15	95 BCE - 20 CE	EF/LF Xakal	
	UCIAMS-172404	Plaza B/12th, Lot PL-B-146, Below Fl. 10	Faunal Bone	2500 ± 20	775–540 BCE	LF Kanluk	
	UCIAMS-172405	Plaza B/10th, Lot PL-B-193, Between Feat. 21 & 26	Faunal Bone	2530 ± 20	795–550 BCE	LF Kanluk	
	UCIAMS-174957	Plaza B/9th, Lot PL-B-180, Below Fl. 13	Faunal Bone	2545 ± 20	800–560 BCE	LF Kanluk	
	UCIAMS-169814	Plaza B/8th, Lot PL-B-176, Feat. 19	Charcoal	2525 ± 15	790–550 BCE	EF Kanluk	
	UCIAMS-169815	Plaza B/5th, Lot PL-B-167, Below Fl. 16	Charcoal	2760 ± 20	975–835 BCE	EF Kanluk	
	UCIAMS-172403	Plaza B/4th, Lot PL-B-168, Below Fl. 17	Faunal Bone	2835 ± 20	1050–925 BCE	Cunil	
	UCIAMS-169816	Plaza B/4th, Lot PL-B-169, Below Fl. 17	Charcoal	2820 ± 15	1015–920 BCE	Cunil	
	UCIAMS-169817	Plaza B/3rd, Lot PL-B-184, Fill/Sascab	Charcoal	2800 ± 20	1010–900 BCE	Cunil	
Other Site Core Radiocarbon Dates							
	AA103355	Structure B1, Burial 7a	Human Tooth	1432 ± 46	140–395 CE	Hermitage	Novotny 2015
	AA103356	Structure B1, Burial 7b	Human Tooth	1516 ± 39	425–620 CE	Hermitage	Novotny 2015
	AA103357	Structure B1, Burial 7c	Human Tooth	1748 ± 47	545–665 CE	Hermitage	Novotny 2015

[a] Denotes radiometric measurement.
[b] Denotes date found unacceptable for context by original investigators.

facet of the Late Preclassic period, suggesting the development of more complex socio-political relationships at Cahal Pech (Awe et al., 2009). Other large, formally organized civic centers were also established during the Late Preclassic throughout the Belize Valley including Blackman Eddy, Xunantunich Group E, Pacbitun, Actuncan, and Barton Ramie (Awe, 1992; Brown et al., 2013; Garber et al., 2004; Healy et al., 2004b; Willey et al., 1965).

While much of the earliest architecture in the Cahal Pech epicenter is buried beneath later monumental Classic period construction, Middle and Late Preclassic household groups surrounding the site center are more accessible for excavation and analysis. Both elite and non-elite residential settlements dating to the Middle and Late Preclassic have been documented to the east and south of the site core. Radiocarbon dates and associated ceramic materials from several of the larger house groups indicate that at least 10 residential groups (Burns Avenue Group, Cas Pek, Ch'um, Melhado, Tolok, Tzutziiy K'in, Zinic, Zopilote, and Zubin) were established by the end of the Middle Preclassic and occupied through the Classic period (Awe, 1992; Awe et al., 2014; Ebert et al., 2016a; Healy and Awe, 1995; Iannone, 1996; Powis, 1996; Willey and Bullard, 1956). More recent pedestrian survey has documented more extensive evidence of Late Middle Preclassic residential settlements to the north and west of Cahal Pech (Ebert et al., 2016b).

3. Materials and methods

3.1. Radiocarbon dating

Samples for AMS ^{14}C dating were recovered from stratified contexts at Cahal Pech during excavations within the site core and from six residential settlement groups. Samples were collected *in situ* from isolated contexts, construction fill, and in association with plaster floors and other discrete architectural features. When possible, carbonized short-lived twig samples were selected for dating to reduce erroneous age assignments from the “old wood effect” (Schiffer, 1986; Kennett et al., 2002). We also selected four samples of faunal remains for direct dating from the upper levels of Plaza B to avoid problems of old charcoal, and to reduce the impact of modern taphonomic disturbance on the radiocarbon measurements. All charcoal and bone samples were prepared along with standards and backgrounds at the Pennsylvania State University

Table 3
Radiocarbon dates for Cahal Pech residential settlements. All samples are charcoal except for X-27038, which dated a human tooth from the Zubin Group (Novotny, 2015).

Sequence	Provenience	Lab #	Conventional ^{14}C age (BP)	Unmolded 2σ cal range (BCE/ CE)	Associated Ceramics	Reference
Burns Avenue Group	S. Trench 1, Unit 1, Lvl. 4	UCIAMS-169809	2020 ± 15	BCE 55–24 CE	EF/LF Xakal	
Cas Pek Group	Str. D1, Floor 7	Beta-77202[a]	2020 ± 140	BCE 390 - 320 CE	LF Xakal	Healy and Awe 1995
	Str. C, Lvl. 11	Beta-77203[a]	2230 ± 50	BCE 400–185	LF Kanluk	Healy and Awe 1995
Martinez Group Str 2	Below Fl. 2	UCIAMS-164867	1345 ± 20	645–760 CE	Tiger Run/ Spanish Lookout	
	Below Fl. 3, on bedrock	UCIAMS-164868	1505 ± 20	435–615 CE	Hermitage	
Martinez Group Str 3	Below Fl. 1	UCIAMS-164866	1425 ± 15	605–655 CE	Tiger Run	
	Below Fl. 2	UCIAMS-150915	1490 ± 20	540–625 CE	Hermitage	Ebert et al., 2016a
Tolok Group	Round Structure, fill	Beta-77201	2370 ± 60	BCE 760–260	LF Kanluk	Healy and Awe 1995
	Str 1, on bedrock	Beta-77199[a]	2220 ± 100	BCE 540 - 5 CE	LF Kanluk	Healy and Awe 1995
	Str. 14, Lvl. 6	Beta-77220[b]	6680 ± 60	BCE 5710–5505	LF Kanluk	Healy and Awe 1995
Tzutziiy Kin Group Str 1	TK-1 5th, final bench const.	UCIAMS-121550	1225 ± 15	710–880 CE	Spanish Lookout	Ebert et al., 2016a
	TK-1 5th, on plaza floor	UCIAMS-121549	1245 ± 20	680–865 CE	Spanish Lookout	Ebert et al., 2016a
	TK-1 4th, fill	UCIAMS-123531	1545 ± 15	425–565 CE	Hermitage	Ebert et al., 2016a
	TK-1 3rd, fill	UCIAMS-121551	1595 ± 15	410–540 CE	Hermitage	Ebert et al., 2016a
	TK-1 2nd, fill	UCIAMS-123530	1770 ± 15	225–335 CE	LF Xakal	Ebert et al., 2016a
Tzutziiy Kin Group Str 2	Terminal const., fill	UCIAMS-123532	1255 ± 15	685–775 CE	Spanish Lookout	Ebert et al., 2016a
	Fl. 3, surface	UCIAMS-121554	1365 ± 15	645–675 CE	Tiger Run	Ebert et al., 2016a
	Feature 1, fill	UCIAMS-121553	1555 ± 15	425–550 CE	Hermitage	Ebert et al., 2016a
	Below Fl. 6	UCIAMS-164869	1880 ± 15	70–210 CE	LF Xakal	
	Below Fl. 7, paleosol	UCIAMS-164870	1865 ± 15	80–215 CE	LF Xakal	
	Below Fl. 7, paleosol	UCIAMS-164871	1890 ± 15	65–205 CE	LF Xakal	
Tzutziiy Kin Group Str 3	Below Fl. 5	UCIAMS-164872	1920 ± 15	50–130 CE	LF Xakal	
	Below Fl. 7, paleosol	UCIAMS-121552	2150 ± 20	BCE 355–110	EF Xakal	Ebert et al., 2016a
Zopilote Group Str 1	Tomb 1 Burial, inside Vessel 10	UCIAMS-169818	1320 ± 15	655–765 CE	Hermitage/ Tiger Run	
	Fill below Fl. 8	UCIAMS-164876	1765 ± 15	230–335 CE	LF Xakal	
	Fill below Fl. 8	UCIAMS-164877	1780 ± 15	170–330 CE	LF Xakal	
	Fill below Fl. 7	UCIAMS-164874	2070 ± 15	BCE 165–40	EF Xakal	
	Fill below FL. 7	UCIAMS-164875	2070 ± 15	BCE 165–40	EF Xakal	
	Surface Fl. 5	UCIAMS-164878	2085 ± 20	BCE 170–45	EF Xakal	
	Surface Fl. 1A	UCIAMS-164873	2175 ± 15	BCE 355–175	EF Xakal	
Zubin Group	Str A1, Burial 3	X-27038	1336 ± 46	620–575 CE	Spanish Lookout	Novotny 2015

[a] Denotes radiometric measurement.
[b] Denotes date found unacceptable for context by original investigators.

Human Paleoecology & Isotope Geochemistry Lab and the University of California-Irvine Keck Carbon Cycle AMS Facility (UCI KCCAMS). Charcoal samples were prepared following standard practices described by Kennett and colleagues (2014). Bone collagen for radiocarbon analyses was extracted using XAD purification to remove all humic and fulvic acids bound to the collagen (Stafford et al., 1988, 1991). All dates in Table 2 and Table 3 are reported as conventional ^{14}C ages corrected for fractionation, with measured δ^{13}C following Stuiver and Polach (1977). Date calibrations and stratigraphic models were produced in OxCal v.4.2 (Bronk Ramsey, 2009) using the IntCal13 Northern Hemisphere atmospheric curve (Reimer et al., 2013). Calibrated and modeled date ranges are 2-σ ranges.

3.2. Bayesian modeling

We developed Bayesian stratigraphic models within OxCal to understand the Preclassic occupational history of Cahal Pech, and other contemporaneous Preclassic period sites in the Maya lowlands (see Supplemental Documentation). Traditional statistical analysis of radiocarbon dates from archaeological contexts has relied on the probability distributions of individual dates to determine the likelihood that two events were sequential or contemporaneous. The Bayesian approach, on the other hand, incorporates *a priori* contextual information obtained in the field to constrain the probability distributions of calibrated dates for each radiocarbon measurement (Bayliss and Bronk Ramsey, 2004; Bronk Ramsey, 2015). This method also takes advantage of architectural stratigraphy and information on ceramic phases by incorporating this data into the models to estimate dates for observed events that cannot be directly dated (e.g., clearing/leveling plazas, construction of plaster floors, remodeling of buildings; Culleton et al., 2012; Ebert et al., 2016a; Higham et al., 2014). While dates were sampled from contexts with associated diagnostic Preclassic materials, the modeled radiocarbon chronologies presented here provide a framework for interpreting patterns of spatial, demographic, and socio-political change between households and the Cahal Pech site core, and to the developmental trajectories of other important Preclassic sites elsewhere in the southern lowlands.

Radiocarbon dates from stratified contexts at Cahal Pech were modeled within ordered *sequences* in the OxCal program within discrete construction phases that separate directly dated deposits, which were modeled as single *boundaries* (i.e., events not directly dated). Additional *boundaries* were placed at the beginning of each sequence to provide an estimate of the time range for the initiation and termination of use of the structure or of site occupation. Dates from Str. B4 were modeled within a single sequence because of the clear stratigraphy present at this building. Units 4 through 5 were excavated from the center part of the summit of Str. B4 during the 1991 BVAR field season, and charcoal samples for radiocarbon dating were collected from Unit 5 (Awe, 1992; Fig. S2). Units 10 and 11 were later excavated in 2012 to recover additional material for direct dating. These units were extended northward into Plaza B to form a trench (Units 12, 13, and 14) in order to expose a larger stratigraphic section for the structure (Ishihara-Brito and Awe, 2013). A total of 13 construction phases have been documented for the building, with the upper strata (Floors 1 and 2, associated with construction phases Str. B4/13th and Str. B4/12th,

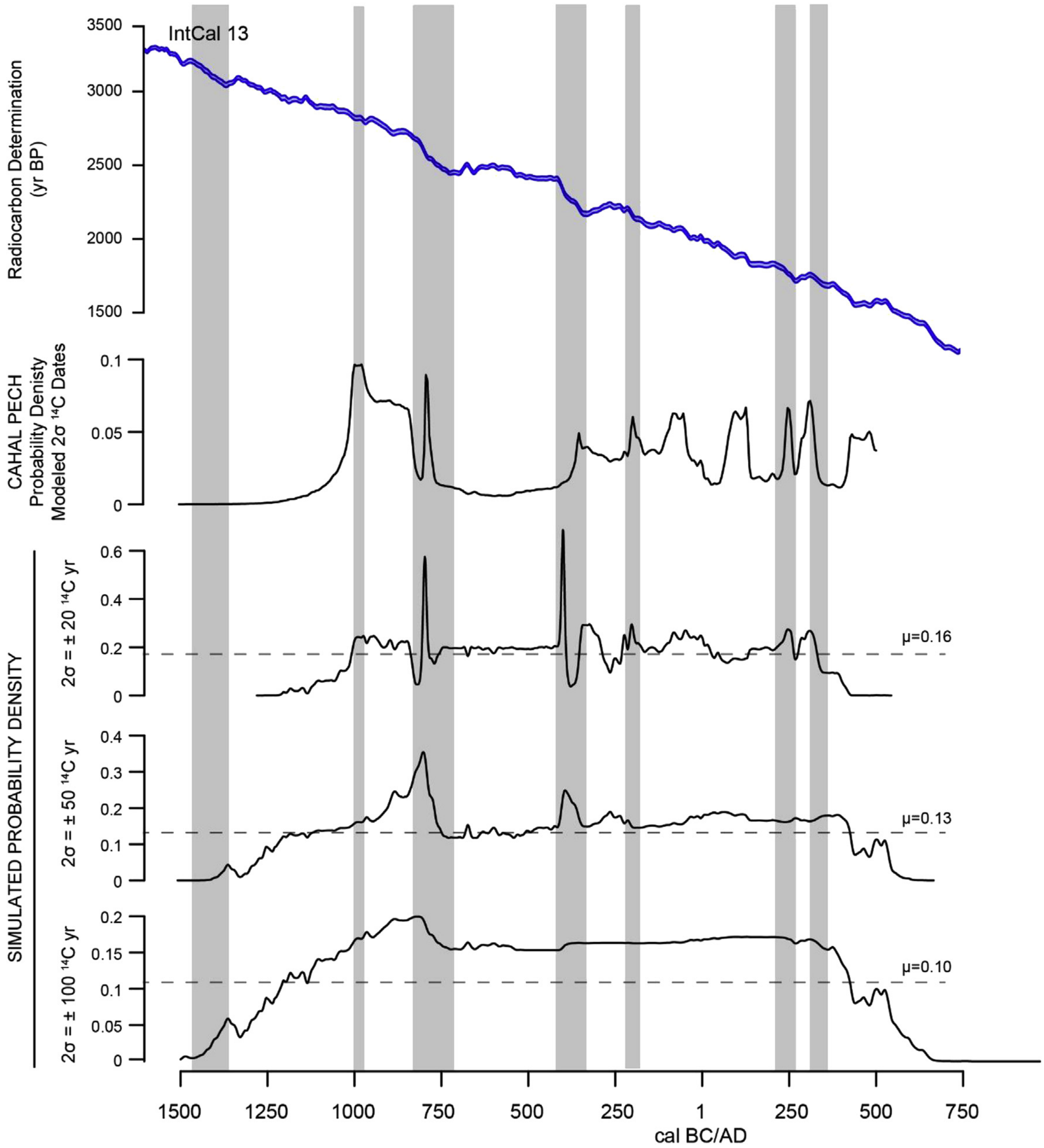

Fig. 4. Simulated summed probability distributions, each calculated for the same $n = 240$ ^{14}C ages using different measurement errors. These are plotted against the summed probability distribution for the Cahal Pech site core and settlement ^{14}C age. Shaded areas represent steep locations in the IntCal13 calibration curve. Dashed lines indicate mean expected probability.

respectively) containing Late to Terminal Classic materials. Four dates were not included in the modeled sequence because they were determined to be either too early (UCIAMS-115022, UCIAMS-111159) or too late (UCIAMS-111160, UCIAMS-111161) for the contexts from which they were recovered. Several of these outlier dates may be the result of a wooden post burned *in situ* sometime during the Preclassic, which distributed charcoal throughout the sequence resulted in several date reversals.

Excavations in the southern portion of Plaza B, along the north walls of Strs. B4 and B5, revealed construction phases spanning the Preclassic through Terminal Classic periods (Peniche May 2016; Fig. S2). The final three phases of construction (Floors 1–3) have been dated to the Classic period based on ceramic associations. A total of nine AMS ^{14}C dates were modeled in a single sequence based on their stratigraphic context to understand the Early through Late Preclassic periods located in the strata below Floor 4. Three dates from contexts between Floors 4 through Floors 6 believed to be Late Preclassic (UCIAMS-169810, UCIAMS-169811, and UCIAMS-169812) returned historic date ranges, likely due to taphonomic disturbance, and were not modeled because they are too late for their context.

A total of 30 radiocarbon dates were derived from six residential settlements within the Cahal Pech hinterland to document the settlement and growth of house groups around the site core. Sequences were modeled in OxCal for the entire Preclassic to Classic occupation of each structure within a residential group that had two or more radiocarbon dates. Models for the Tzuztiiy K'in Group were modified after Ebert et al. (2016a), with the addition of four dates from buildings across the residential group. Seven dates were modeled for Str. 1 at the Zopilote Group, and four dates were modeled for Strs. 2 and 3 at the Martinez Group.

Radiocarbon dates from other known Preclassic sites in the southern lowlands were also collected from the published literature to compare their developmental trajectories with that of Cahal Pech. Dates come from five core regions in the southern Maya lowlands: (1) the Belize Valley and Vaca Plateau, (2) Northern Belize, (3) the Pasión region, (3) the Petén and Southern Belize region, and (5) the Southeastern periphery. Core regions roughly correspond to major geographical regions in the Maya lowlands, as well as to the spatial extent of pre-Mamon ceramic traditions (Clark and Cheetham, 2002: Fig. 5) and later shared Classic period ceramic, architectural, and epigraphic traditions. We placed sites in the Petén and Southern Belize within the same dataset based on ceramic and epigraphic data that suggests polities in the southwestern portion of Belize were politically and economically linked to the Petén, and especially the site of Tikal, during the Preclassic through Classic periods (Prufer et al., 2011; Wanyerka, 2009). We also include the site of Palenque (Chiapas, Mexico) in this data set due to its relative geographic proximity to the Petén compared to other parts of the lowlands. There is also a dearth of direct radiocarbon dates from other Chiapas sites, and placing Palenque within the Petén dataset helps to better contextualize the site's developmental trajectory during the Preclassic. The Southeastern periphery encompasses sites the central and western portions of the modern countries of Honduras, eastern Guatemala, and El Salvador (after Urban and Schortman, 1986).

Supplementary Table 1 reports 1196 radiocarbon dates organized by core region and by site. Associated information was recorded for each date, including the site name and core region, contextual information (specific stratigraphic and spatial relationships), type of material dated (e.g., charcoal, human remains, faunal remains), laboratory sample number, conventional ^{14}C date and error ranges, 2-σ calibrated distributions, whether the sample was dated via Accelerated Mass Spectrometer (AMS) or radiometric ^{14}C dating (if reported), and the reference publication.

Dates were subjected to chronometric hygiene criteria established by Hoggarth and colleagues (2016:31) to eliminate questionable dates with large error ranges and/or unknown contexts, and to constrain modeled distributions. We applied Bayesian statistics to sets of dates for each site to produce modeled sequences in OxCal *only* when stratigraphic and other contextual information was available. Dates derived from contexts in stratigraphic association were modeled using the *Sequence* and/or *Phase* commands in OxCal. In cases with dates from stratified contexts that did not pass the chronometric hygiene standards, we assess the statistical fit between the date and associated samples before eliminating them from modeled sequences. Some dates in our large ^{14}C dataset fall after the Preclassic period (conventional ^{14}C yr younger than 1700 BP), and therefore were not considered in our modeled sequences unless they could be tied to an earlier Preclassic sequence for a given site based on stratigraphic associations. We list Classic through Postclassic period dates falling after 1700 BP for use in future studies. The results of radiocarbon chronological models for different sites and regions serve as initial hypotheses concerning the timing and tempo of cultural activities (e.g., construction activity, placement of burials), which can be tested against additional temporal and archaeological data as they become available. When available we also used previously published Bayesian chronologies for Preclassic lowland sites (e.g., Ceibal, Inomata et al., 2017; Lamanai, Hanna et al., 2016; Uxbenká, Culleton et al., 2012). Descriptions of chronometric hygiene results and Bayesian radiocarbon models are reported in Table S3 by region and site.

3.3. Summed probability distributions

Cumulative probability distributions of calibrated radiocarbon dates ("summed probability distributions") have been applied to radiocarbon datasets as a proxy for human activity and to understand culture change worldwide. Summed probability distributions have most frequently been used to identify local and regional population and cultural trends in North America (e.g., Buchanan et al., 2008; Kelly et al., 2013), Europe (Armit et al., 2013; Collard

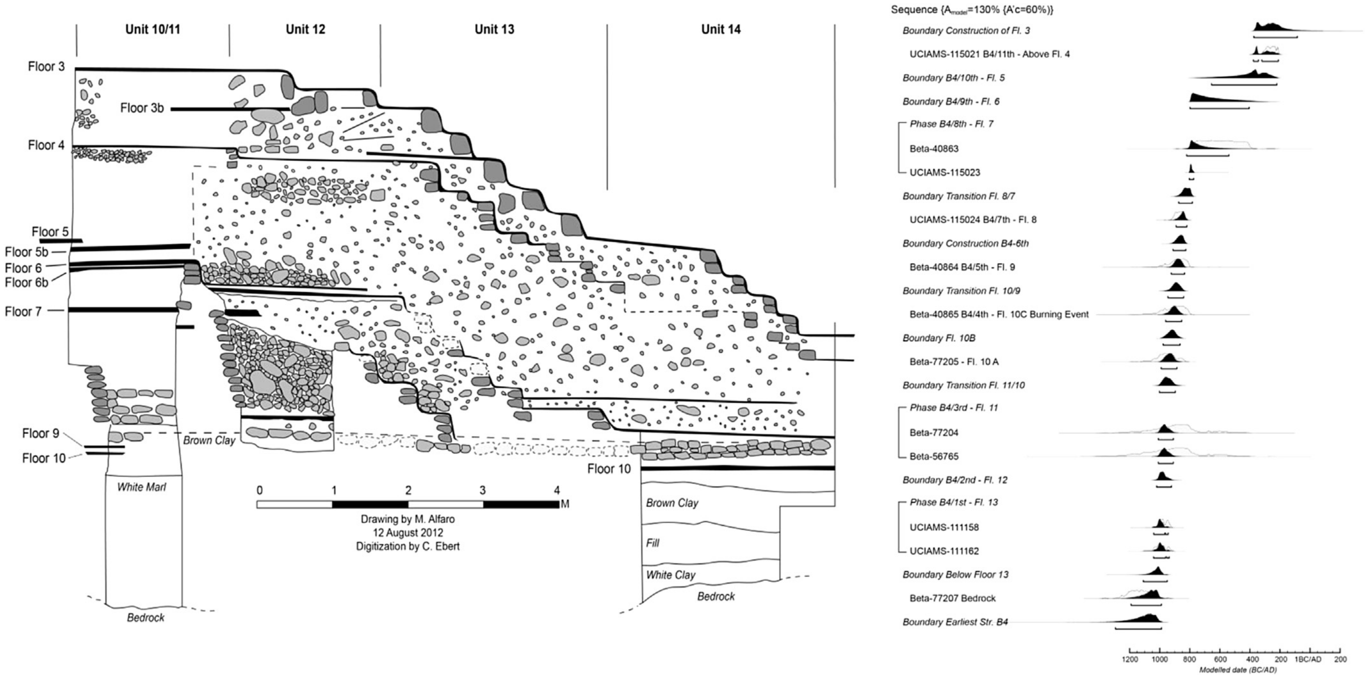

Fig. 5. Profile and modeled ^{14}C dates for Cahal Pech Str. B4. Prior distributions are shown in gray.

et al., 2010a,b; Gkiasta et al.,. 2003; Hinz et al., 2012; Shennan et al., 2013; van Andel et al., 2003), Mesoamerica (Hoggarth et al., 2016), South America (Goldberg et al., 2016), China (Wang et al., 2014), and Australia (Holdaway et al., 2009). The application of summed probability distributions for the reconstruction population histories, however, has met with criticisms since it is often difficult to determine whether the abundance of radiocarbon dates is necessarily proportional to population size and the intensity of occupation (Attenbrow and Hiscock, 2015; Contreras and Meadows, 2014; Culleton, 2008; Kennett et al., 2008). Hoggarth and colleagues (2016; see also Kennett et al., 2014) have argued instead that summed probability distributions of radiocarbon dates sampled from specific contexts, in conjunction with other types of archaeological data (e.g., architectural, ceramic), can be used as a heuristic tool to identify important negative and positive trends (i.e., "tipping points") of activity at a particular context, site, or within a region. Following this premise, we argue that summed probabilities do not represent occupational intensity or serve as proxies for population levels. Rather, we selected dates from primary contexts when possible, including construction episodes, based on the assumption that dates within a summed distribution represent discrete events (Williams, 2012). For Cahal Pech, we suggest that the summed probability distributions of radiocarbon dates from different construction events, considered alongside other architectural, ceramic, and paleoclimate proxy data yields an approximation of the initiation and cessation of building activity. The timing and tempo of construction correspond to social and political trends identified in the archaeological record at the site during the Preclassic.

Calibrated radiocarbon dates and summed probability distributions can also be impacted by small sample size and data density (Williams, 2012), measurement precision (Contreras and Meadows, 2014; Hinz et al., 2012), and the radiocarbon curve (Bamforth and Grund, 2012; Culleton, 2008), which can potentially introduce biases into interpretation. Williams (2012: 581) suggests that small numbers of non-systematically sampled ^{14}C dates ($n < 200$), with large associated uncertainties (>±100 yr), can potentially produce variability within summed probability distributions (see also Michczyńska and Pazdur, 2004). Timpson and colleagues (2014; see also Shennan et al., 2013) have demonstrated, however, that summed distributions of small number of randomly sampled dates (less than 20) from a larger radiocarbon dataset show similar positive and negative trends when compared to the summed distribution of the larger dataset. A recent study examining the Terminal Classic collapse in the northern Maya lowlands, showed a strong correspondence between smaller sample sizes of modeled ^{14}C dates to socio-political trends recorded independently within hieroglyphic texts and paleoclimate records (Hoggarth et al., 2016). To address the issue of sample size for the Preclassic in the southern lowlands, we similarly systematically selected and modeled dates from discrete contexts for complete stratigraphic architectural sequences within the Cahal Pech site core and settlement. Additionally, the number of dates from Cahal Pech ($n = 62$) represents one of the largest ^{14}C datasets from the Maya region (see Culleton et al., 2012; Inomata et al., 2017; Prufer et al., 2017 for other examples). Future radiocarbon work from the site will increase this sample size and help to refine the shape of the summed probability distribution in order to clarify the timing of important events related to the site's development.

Maya Preclassic period dates also fall on several steep slopes and plateaus (less steep) in the radiocarbon curve that have reverse affects upon the form of summed probability distributions. While dates intersecting steeper parts of the curve tend to be overrepresented, resulting in peaks in summed probability distributions, plateaus cause calibrated date ranges to be underrepresented within larger datasets (Higham, 2007; Michczynski and Michczynska, 2006; Weninger et al., 2011). In particular, the period between 700 and 400 cal BCE (2500-2400 yr BP), often referred to as the "Hallstatt Plateau" in Old World archaeology (Hajdas, 2008), produces large calibrated date ranges up to 500 calendar years regardless of measurement precision. The effect of this plateau on radiocarbon chronologies has been of concern to European and Near Eastern archaeologists (e.g., Cook et al., 2010; Hamilton et al., 2015), but remains relatively unexplored in the Maya region despite its significant impact on our understanding of directly dated Middle Preclassic events.

We examined biases introduced by plateaus in the calibration curve on the summed probability distribution of radiocarbon dates from Cahal Pech in two ways. First, calibrated distributions were plotted against a histogram showing the number of calibrated 2-σ ^{14}C dates binned in 50-year intervals. These data show general positive and negative trends in the summed distributions with attached confidence intervals. Second, we performed a sensitivity test and simulated radiocarbon ages from 1300 cal BCE and cal 300 CE (3000-1600 cal BP). The *R Simulate* in OxCal command was used to specify a calibrated age and a measurement error, which translates the age through the calibration curve to generate a conventional radiocarbon age (yr BP), and then calibrates the simulated conventional age. We developed three separate models to simulate dates at multiple precision levels (±20, 50, and 100 ^{14}C yr). A total of 10 dates were simulated for every 50 calibrated years (total $n = 240$) for each model. Comparing the three simulated models, fluctuations in the calibration impose some structure on a random sample of conventional ages through the modeled period (Fig. 4). Conventional ages between ~750 and 400 cal BCE (2500-2400 BP), during the Hallstatt Plateau, are less common while dates on either side are more common. Other steep sections of the curve at approximately 1000 cal BCE (~2900 BP), 250-150 cal BCE (2200–2100 BP), cal 200 CE (1750 BP) also produce spikes in the simulated summed probability curves, resulting in dates becoming more common in the distribution. The span between 150 cal BCE-cal 50 CE(2100 and 1900 BP) is characterized by high variability in the calibration curve, which is also reflected in the simulated probability distributions. Measurement errors of conventional radiocarbon ages also affect the structure of simulated probability densities. As the error range increases, the intensity of peaks and troughs in the summed probabilities diminishes. This suggests that more precise measurements are necessary to identify a single event within the radiocarbon chronologies. A Pearson's R correlation test of modeled radiocarbon dates for Cahal Pech against the highest-resolution simulated frequency (±20 ^{14}C yr; Supplemental Fig. S3) suggests that although the overall structure of the probability distribution for Cahal Pech is partly driven by the shape of the calibration curve, the probability distribution is not completely explained as an artifact of the curve.

4. Results

4.1. Chronology for Cahal Pech site core

Excavations and AMS ^{14}C dating indicate that Cahal Pech was settled by the end of the Early Preclassic, and was inhabited continuously through the Terminal Classic period (Fig. S4). The earliest direct date from the site comes from Str. B4 and dates to 1205-990 cal BCE (Beta-77207). The sample was recovered beneath Floor 13 on the surface of bedrock, which was likely leveled prior to initial construction at Cahal Pech (Fig. 5 and Table S2; Awe, 1992; Peniche May 2016). A *boundary* at the beginning of the Str. B4 modeled sequence estimates that this leveling event may have occurred as early as 1325-985 cal BCE. After the initial founding of the site, the modeled stratigraphic sequences show that late Early

Preclassic construction was rapid at both Str. B4 and within Plaza B. Activity during this time is associated with the construction of agrarian residences at the site, which consisted of the remodeling of a series of superimposed living surfaces composed of tamped earth floors supporting wattle-and-daub superstructures (Awe, 1992; Healy et al., 2004a; Horn, 2015; Peniche May 2016; Sullivan and Awe, 2013). These domestic buildings are located below Floor 10 at Str. B4 (B4/1st – B4/4th; Awe, 1992: 133–135) and below Floor 17 within Plaza B (Plaza B/1st through Plaza B/4th; Peniche May 2016:150–154). Archaeological data indicate a shift in the use of space beginning after 950 cal BCE at Str. B4. During this time, Str. B4 underwent several modifications (B4/5th – B4/7th) terminating with the construction of a specialized round structure measuring approximately 1.5 m in height and dating to 895-820 cal BCE (Beta-40863; Healy and Awe, 1995) likely used for public ceremonies (Aimers et al., 2000).

During the early Middle Preclassic, new styles of large public architecture and high-status residences began to replace small Early Preclassic domestic structures at other locations in the site core (Aimers et al., 2000; Awe, 1992; Peniche May 2016). In Plaza B, a second phase of construction (Plaza B/8th-Plaza B/12th) occurred during this interval (Fig. 6 and Table S2; Peniche May 2016). Radiocarbon dates from this phase, however, are impacted by the Middle Preclassic radiocarbon curve plateau (Hallstatt Plateau) and possess large calibrated error ranges (~200 years), obscuring the precise timing of these events. Ceramic associations, however, place phase Plaza B/8th during the end of the early Kanluk ceramic phase (~750-650 cal BCE; Peniche May 2016). Phases Plaza B/9–12th are associated with ceramics that date to the late facet of the Kanluk ceramic phase (~650-550 cal BCE). Phase Plaza B/9th

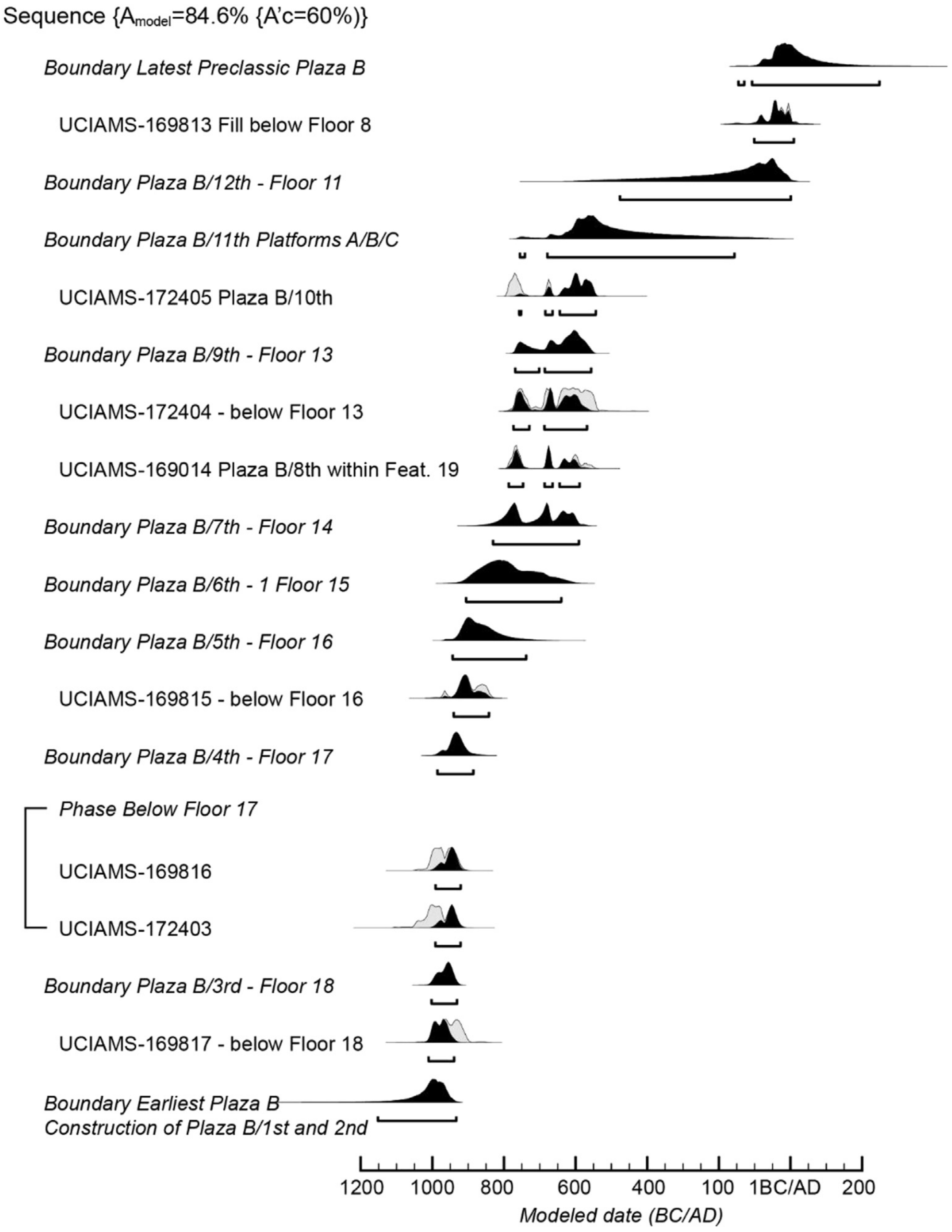

Fig. 6. Modeled ^{14}C dates for Cahal Pech Plaza B. Prior distributions are shown in gray.

(Floor 13) represents the first in a series of low rectangular platforms that may have served as higher-status residences. The next construction, Plaza B/10th (Floor 12) enlarged the first rectangular platform, and a retaining wall composed of at least five courses of regularly cut limestone blocks was placed on the building. Plaza B/11th consisted of the construction of a specialized keyhole-shaped round structure. A second large building was also built to the west of the round structure, and may have served as an associated residence for a high-status family. The last Middle Preclassic construction episode within Plaza B (Plaza B/12th, Floor 11) was an extensive cobble platform (~98 m^2) covering the keyhole structure that was placed sometime between 765 and 535 cal BCE. Similar cobbled platforms may have existed in several areas across the plaza in antiquity (Horn, 2015; Peniche May 2016). While the pace of the second phase construction in Plaza B is unknown, the cessation of these activities may correspond with a century-long dry period between 600 and 500 cal BCE documented in both the Macal Chasm and Itzamna speleothem records.

Construction phases Str. B4/8th through Str. B4/10th occurred at the end of the Middle Preclassic and into the Late Preclassic, with remodeling of monumental buildings occurring at punctuated intervals between 600 and 200 cal BCE (late facet Kanluk to early facet Xakal ceramic phases). The building corresponding with Str. B4/8th (Floors 7A and 7B) consisted of a 3 m tall circular platform made of cut limestone blocks. Two dates (Beta-40863; UCIAMS-115023) from the surface of Floor 7 were modeled within a *Phase* in the Str. B4 sequence and produced calibrated date ranges between 805 and 440 cal BCE. During the construction of Str. B4/9th, a plastered surface corresponding to Floor 6 replaced Floor 7. The subsequent placement of Floor 5 (Str. B4/10th) raised the building ~1.2 m above the surface of Str. B4/8th, and the plaza floor was elevated 0.5 m (Ishihara-Brito and Awe, 2013:127). Two low masonry walls of a small building were placed on the summit of this platform. The events corresponding to construction of Str. B4/9th and B4/10th were not directly dated due to a lack of datable materials recovered from excavations, but likely occurred over a longer span of time from 795 to 280 cal BCE. A single radiocarbon date below Floor 8 in Plaza B provides evidence for construction activity in this part of the site through at least the middle of the Late Preclassic between 105 cal BCE and cal 15 CE (UCIAMS-169813). Relatively little Late Preclassic and Early Classic materials were recovered from the Plaza B excavations (Peniche May 2016), and archaeological data also indicate a hiatus in activity at Str. B4 until the Late Classic (Awe, 1992; Healy et al., 2004a). Excavations at Str. B5, located to the west of Str. B4, exposed a Late Preclassic building, perhaps suggesting that construction activity shifted when the plaza was expanded during the Late Preclassic (Peniche May 2016).

4.2. Chronology for Cahal Pech settlement

Radiocarbon dating indicates that there was limited activity within the Cahal Pech settlement zone prior to cal BCE 400, though ceramic data from excavations provide some evidence for permanent settlement earlier during the Cunil phase (Ebert and Fox, 2016; Iannone, 1996). At the Zopilote Group, located ~0.75 km south of the site core, the first documented construction consisted of a plaster floor (Floor 1A) placed between 355 and 170 cal BCE (UCIAMS-164873) above earlier Cunil phase deposits, containing high frequencies of residential debris (utilitarian ceramics, freshwater shells, chert cores and flake tools) in a paleosol layer beneath Str. 1 (Fig. S5). Iannone (1996) also recovered Cunil materials in the lowest stratigraphic levels of the Zubin Group. Similar Preclassic contexts have been encountered throughout the Maya lowlands and represent the first soils encountered by initial settlers of a region (Beach et al., 2006). Radiocarbon dates and ceramic evidence indicate that the scale of settlement around Cahal Pech increased during the second half of the Middle Preclassic (Willey and Bullard, 1956; Awe, 1992:207; Iannone, 1996; Powis, 1996). Four dates from two peripheral settlements, the Cas Pek and Tolok Groups, date the earliest activity at these settlements from 530 to 400 cal BCE. Radiocarbon dating from the Tzutziiy K'in Group, located approximately 1.8 km directly west of the Cahal Pech site core, document settlement of that house group prior to the Late Preclassic (325-110 cal BCE; Ebert et al., 2016a).

Subsequent larger-scale residential and non-residential construction occurred after 350 cal BCE during the Late Preclassic Xakal ceramic phase (Ebert and Fox, 2016; Healy and Awe, 1995; Healy et al., 2004a). The construction of several low masonry platforms at the Zopilote Group (ZPL-1/1st through ZPL-1/6th), which likely functioned as public temple buildings, were constructed between 170 and 40 cal BCE. The next burst of construction occurred between cal 170–335 CE, and involved the consecutive construction of two large temples (ZPL-1/7th and ZPL-1/8th). The construction of these larger public buildings within residential groups occurred in the context of punctuated drought events from 165 to 1 cal BCE. Multiple masonry platforms were also built in the main plaza at Tzutziiy K'in during the middle of the Late Preclassic, corresponding with a wet climatic interval. At Str. 1, a low plastered platform was constructed between 45 cal BCE-cal 330 CE, and may have functioned as a domestic structure for a high-status family (Ebert et al., 2016a). Cobble platforms similar to those in Plaza B of the Cahal Pech site core are also present at Tzutziiy K'in, dating slightly later to cal 65–215 CE (late facet Xakal ceramic phase). Ceramic associations suggest that this pattern of Late Preclassic growth is consistent with several other large house groups (e.g., Zubin, Zopilote, and Cas Pek Groups) throughout the hinterlands of Cahal Pech.

Smaller scale residential occupation during the Late Preclassic and into the Early Classic has also been documented around the Cahal Pech site core (Awe, 1992; Healy et al., 2004a; Ebert et al., 2016a,b; Ebert and Fox, 2016). Modern-day sewer construction along Burns Avenue in the downtown area of the town of San Ignacio and subsequent salvage excavations documented the presence of several deposits of cached vessels and human remains that were likely associated with a residential settlement in this location (Awe et al., 2014). A radiocarbon date of 55–25 cal BCE (UCIAMS-169809) and ceramic associations place the occupation of the Burns Avenue Group during the early and late facet transition of the Xakal ceramic phase. The presence of sterile alluvial deposits above Late Preclassic contexts document the abandonment of this settlement group shortly after this time, perhaps due to flooding from the nearby Belize River (Awe et al., 2014).

Settlement research and radiocarbon dating document the establishment of new residential groups during the Early Classic (Ebert et al., 2016a), indicating continued population growth from the Preclassic into the Early Classic after the extended Late Preclassic drought. Four radiocarbon dates place settlement at the Martinez Group, south of the Cahal Pech site core, during the Early Classic (cal 435–615 CE; UCIAMS-164868) with continued growth into the Late Classic period. Early Classic components were also added in the Cahal Pech site core and several settlement groups, including relatively large domestic and non-domestic architecture (Ebert et al., 2016a; Iannone, 1996; Powis, 1996; Awe and Helmke, 2005). By the Late Classic, the Cahal Pech settlement system had become considerably more stratified and complex, with over 140 house groups located around the site core (Ebert et al., 2016b).

4.3. Summed probability distributions for the southern Maya lowlands

We developed Bayesian radiocarbon models and summed probability distributions from sites across the southern Maya lowlands to provide evidence for the timing and tempo of cultural activity during the Preclassic period. These data can be compared to paleoclimate proxy records to help interpret the climatic contexts of site growth and decline (Kennett et al., 2013; Hoggarth et al., 2016). Fig. 7 shows a comparison of the summed distributions of modeled radiocarbon sequences for the Cahal Pech core in relation to the settlement area, with prolonged dry events documented in Preclassic paleoclimate proxy records also highlighted. The probability distributions for Str. B4 and Plaza B show a sharp increase

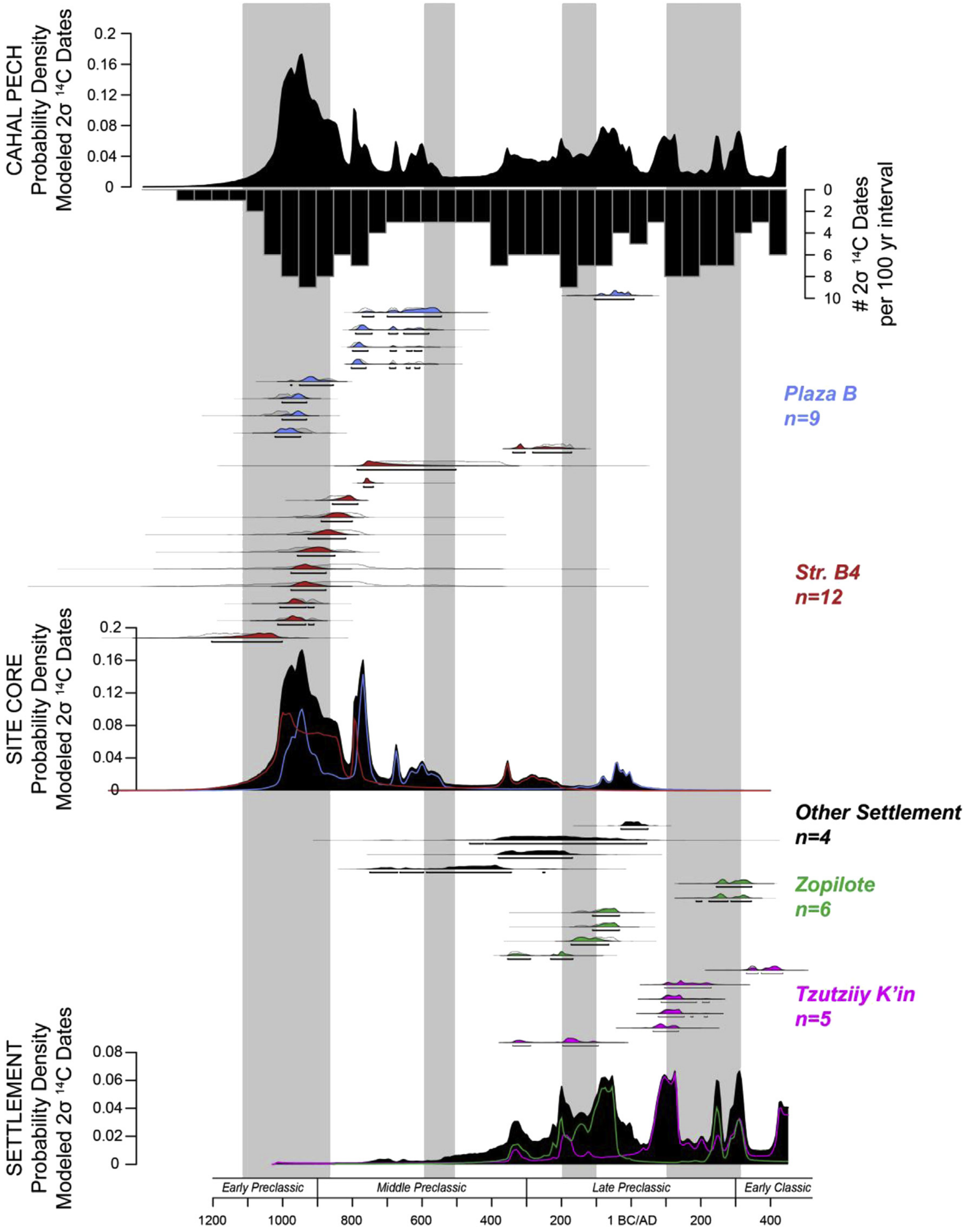

Fig. 7. Summed probability distributions of all modeled and unmodeled radiocarbon dates from the Cahal Pech site core and settlement, shown with a histogram of radiocarbon dates in 50-year bins. Modeled and unmodeled dates at individual locations across the site are also shown with the summed probability distributions. Multi-century major dry events documented in paleoclimate records are highlighted in gray.

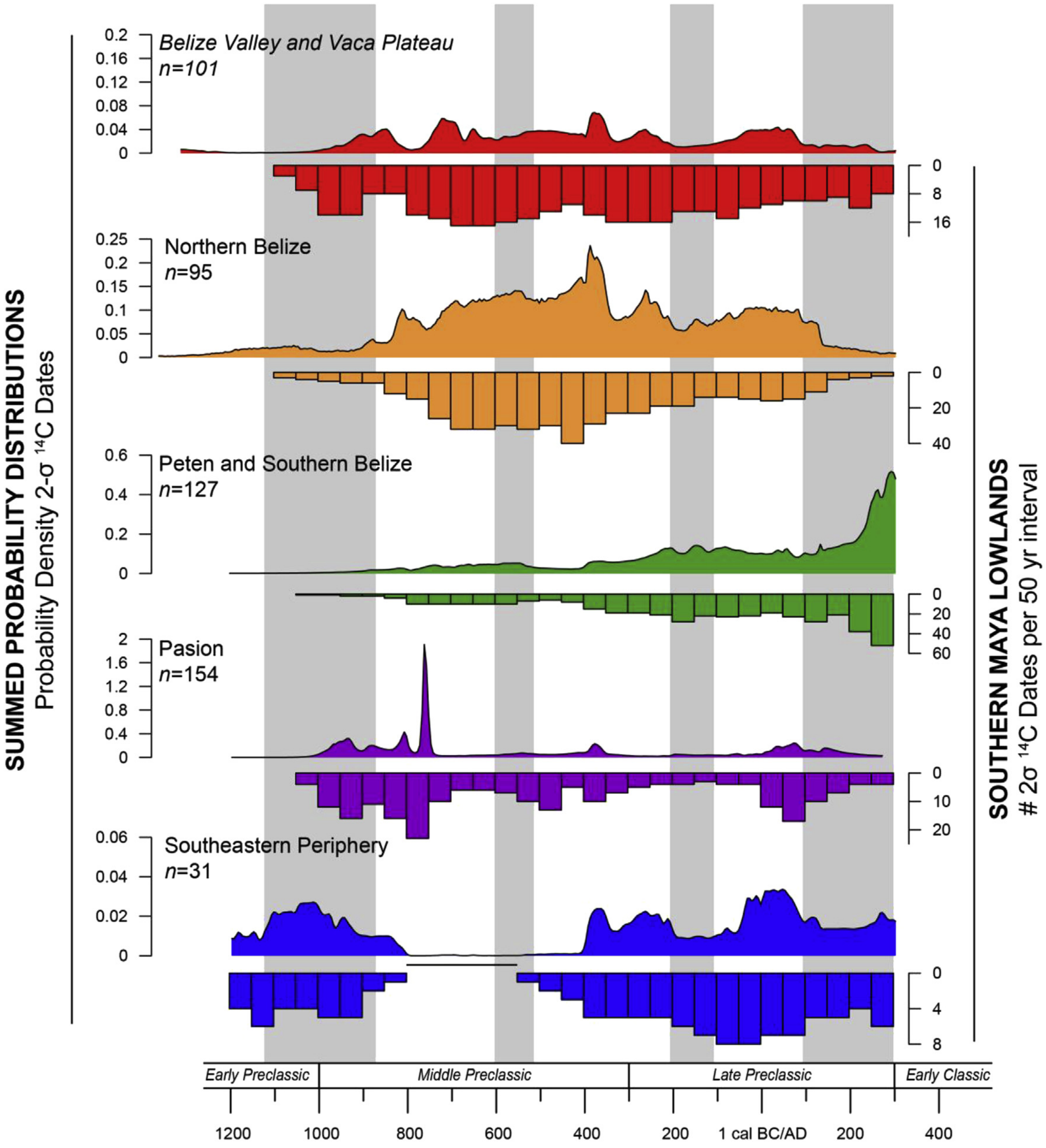

Fig. 8. Summed probability distributions of Preclassic radiocarbon dates from five core regions in the southern Maya lowlands including (1) the Belize Valley and Vaca Plateau, (2) Northern Belize, (3) the Pasión region, (3) the Petén and Southern Belize, and (5) the Southeastern Periphery. Histograms showing the number of calibrated 2-ó ^{14}C dates binned in 50-year intervals, are plotted below each summed distribution. Multi-century major dry events documented in paleoclimate records are highlighted in gray.

beginning around 1100 cal BCE, with a subsequent peak at 1000 cal BCE corresponding with high levels of domestic construction towards the end of the Early Preclassic. Early domestic occupation of the site core occurred during a multi-century dry period recorded in both northern (Curtis et al., 1996; Hodell et al., 1995; Medina-Elizalde et al., 2016) and southern lowland paleoclimate records (Akers et al., 2016; Webster et al., 2007).

A second peak in building activity occurs in the summed distributions for the Cahal Pech site core from 800 to 750 cal BCE, and corresponds with a steep portion of the calibration curve that may cause dates to be over-represented. For Str. B4, the peak likely marks a decline in construction at that building. For Plaza B, however, the peak corresponds with the second pulse of activity consisting of a series of large platform buildings that likely functioned as public buildings and high-status residences. Smaller pulses of activity punctuate the site core summed distribution through the end of the Middle Preclassic and into the Late Preclassic. These low peaks represent isolated construction events of public buildings, which occur during relatively wet periods in regional paleoclimate records. At the end of the Late Preclassic, construction of Str. B4 and Plaza B is discontinued, coinciding with the onset of the multi-century Late Preclassic drought. Archaeological evidence indicates a shift in construction activities starting at this time, focusing monumental building in other parts of the site core (Awe, 1992). The summed distribution for the Cahal Pech settlement mirrors an increased level of activity outside the site core beginning in the Late Preclassic period (Ebert et al., 2016a). The summed distribution for the Zopilote Group shows increasingly larger peaks from 350 to 1 cal BCE, corresponding with large scale modifications of the Str. 1 temple building within this group. There is a gap in the Zopilote distribution between ~ cal 1–200 CE, when construction at the Tzutziiy K'in Group reached its highest levels during the Preclassic. Alternating peaks in the summed probabilities for these larger residential settlements demonstrate variability in growth that was likely impacted by household-specific social and economic factors, and perhaps climate conditions.

The radiocarbon chronology and summed distribution of modeled dates for Cahal Pech can be compared to radiocarbon chronologies from archaeological sequences in other parts of the Maya lowlands to provide a broader context for alternating periods of development and decline of specific polities and the role of climate change in these developments. Modeled and unmodeled radiocarbon dates ($n = 367$) from a total of 36 sites were used to create summed probability distributions for five core regions in the southern Maya lowlands (Fig. 8). The summed distribution of 101 radiocarbon dates from 12 sites in the Belize Valley and Vaca Plateau region, located in the western portion of Belize, shows pulses of construction activity beginning first in the Early Preclassic at Cahal Pech. Activity in this part of the lowlands remains relatively stable through Middle and Late Preclassic periods, despite climatic fluctuations. There is some evidence for a hiatus of monumental construction at the sites of Blackman Eddy (Brown and Garber, 2005; Garber et al., 2004), Chan (Kosakowsky, 2012), Lower Barton Creek (Kollias, 2016), and Xunantunich Group E (Brown et al., 2011) during the prolonged Late Preclassic drought, represented by a decline in the regional summed probability distribution after cal 100 CE. A similar pattern exists in the regional summed distribution for Northern Belize, which was based on 95 radiocarbon dates from 11 sites. While some earlier Archaic period dates exist for Northern Belize, the first evidence for Early and Middle Preclassic agrarian settlement comes from the sites of Colha (Iceland, 1997; Lohse, 2010) and Cuello (Hammond, 2009) between ~1300 and 900 cal BCE. A rapid increase of dates beginning around 800 cal BCE in this region parallels archaeological evidence for the first large-scale construction activities within the monumental epicenters of these sites, in addition to several others (e.g., K'axob, McAnany and Lopez-Varela, 1999; San Estevan, Rosenswig and Kennett, 2008). A dry period spanning from 200 to 100 cal BCE coincides with a decline of dates for this region. The summed distribution drops significantly after cal 100 CE, suggesting that drought had a much more critical impact on local communities in Northern Belize compared to the Belize Valley.

Radiocarbon data for other parts of the lowlands show more variability in patterning. The summed distribution for the Pasión region is composed of modeled and unmodeled Preclassic ^{14}C dates ($n = 154$) primarily from the site of Ceibal (after Inomata et al., 2017). The first directly dated evidence for settlement and construction at Ceibal occurs around 1000 cal BCE (Inomata, 2017; Inomata et al., 2017). An exaggerated peak in the summed probability distribution occurring around 800 cal BCE is driven partially by the calibration curve but also reflects excavation strategies focused on documenting early monumental constructions in site's epicenter (Inomata et al., 2013, 2015). Inomata and colleagues (2017) have also documented a significant population decline at Ceibal and other nearby sites with directly dates contexts (e.g., Caobal, Punta de Chimino) based on architectural and ceramic data beginning in the Late Preclassic around cal 75 BCE, after an interval of intensified conflict with neighboring groups. They suggest that populations continued to decline, so that by cal 300 CE, only a small community remained at the site. This pattern is reflected in the summed probability distribution in the regions as a slight decline beginning around cal 100 CE and continuing through cal 300 CE.

The summed distribution for the Petén and Southern Belize region is composed of 127 dates from ten sites. Very few dates are available for the region prior to 400 cal BCE, when a rise in the summed probability distribution first appears. The earliest reported dates between 1600 and 1000 cal BCE for the region come from the large Preclassic site of Nakbe (Hansen, 2005), though no clear associated contextual or stratigraphic information is reported and therefore we were not able to model these dates. A small number ($n = 3$) of dates falling between 900 and 735 cal BCE are associated with the early occupation of Tikal (Ralph and Stuckenrath, 1962; Stuckenrath et al., 1966) and Cival (Estrada-Belli, 2006, 2008) in the Petén. Dates become more frequent in the Petén and Southern Belize summed distribution after 400 cal BCE, corresponding to a humid phase at the end of the Middle Preclassic. The earliest evidence of hieroglyphic writing from the site of San Bartolo dates slightly after this time, around 300 cal BCE (Saturno et al., 2006). A sharp dip appears in the summed probability between cal 100–200 CE, which may be attributed to changes in the radiocarbon curve. A peak occurring between cal 200–300 CE after the extended Late Preclassic drought, however, is driven by a large number of dates associated with the first monumental constructions at the southern Belize site of Uxbenká (Aquino et al., 2013; Culleton et al., 2012; Prufer et al., 2011, 2017), which is located in one of the wettest parts of the Maya lowlands.

A small set of published radiocarbon dates ($n = 31$) for four sites in the Southeastern Periphery (Honduras and eastern Guatemala) document early settlement along the southern fringe of the Maya lowlands. The earliest dates from this region come from levels corresponding with Archaic period occupation by mobile hunter-gatherers and horticulturalists at El Gigante Rock Shelter (Scheffler et al., 2012). During the Preclassic, radiocarbon dates from the early coastal fishing-farming village of Puerto Escondido record low-level occupation in the region (Joyce and Henderson, 2001). A gap in the summed distribution between 800 and 400 cal BCE can likely be attributed to the paucity of radiocarbon dates from Preclassic sites in this part of the lowlands. After 400 cal BCE the summed probability indicates continuous and steady activity through the end of the Late Preclassic period, albeit at low levels, when the first dates from the Copan Valley (Manahan and Canuto, 2009) and the nearby site of Quirigua (Ashmore, 2007) appear in the regional radiocarbon record.

5. Discussion

The formation and breakdown of complex societies in multiple regions of the world occurred over the last 8000 years, and was dependent upon interacting economic, demographic, and political factors. Climate change on decadal and century-long scales is now recognized as another important force in shaping the historical dynamics of these societies (de Menocal, 2001; Buckley et al., 2010; Kennett and Marwan, 2015). Severe droughts are documented in paleoclimate proxy records for the Preclassic across the Maya lowlands, though the role they played in the episodic formation and breakdown of complex societies is not well explored. Integrating more precise and accurate chronologies based on radiocarbon dates with other lines of evidence (i.e., ceramic, architectural) is essential for understanding the timing and tempo of Preclassic period societal change and its relationship to climate change (Douglas et al., 2016a). In this study, we developed a Bayesian radiocarbon chronology for the Cahal Pech monumental site core and surrounding residential settlement groups to document the episodic growth of social hierarchy at the site in relation to several periods of acute and prolonged drought during the Preclassic. This chronology is complemented by a larger dataset of radiocarbon dates from Preclassic cultural contexts at sites across the southern Maya lowlands ($n = 1196$) compiled from published literature. Bayesian chronologies and summed probabilities of radiocarbon dates developed from this larger dataset help to identify major “tipping points” in

Preclassic cultural and climate change, and to place the Preclassic development of Cahal Pech within a broader regional context.

Our analyses of radiocarbon data for Cahal Pech and other southern lowland sites suggest that the transition to settled village life during the Early Preclassic period was likely variable, though small agricultural villages were present in most parts of the lowlands by 1000 cal BCE. In Belize, radiocarbon dates suggest continuity between Archaic period (1500-1200/1000 cal BCE) mobile hunter-gatherer populations and the first Early Preclassic farming village communities (Clark and Cheetham, 2002; Iceland, 1997, 2005; Lohse, 2010; Stemp et al., 2016; see also Rosenswig, 2015). The first directly dated ceramics in the Belize River Valley (Cunil ceramic complex) come from Cahal Pech (1280-980 cal BCE; Awe, 1992; Sullivan and Awe, 2013), Xunantunich Group E (1220-925 cal BCE; Brown et al., 2011), and Actuncan (1195-995 cal BCE; LeCount et al., 2017), and appear slightly later at the site of Blackman Eddy (990-800 cal BCE; Garber et al., 2004). The Cunil ceramic complex is one of the earliest known in the Maya region, and its appearance at the end of the Early Preclassic signals an increased commitment to maize agriculture and the first permanent settlement in the southern Maya lowlands. Inomata (2017; see also Lohse, 2010) has suggested that the lower most levels at Cahal Pech, which have been found to pre-date 1000 cal BCE based on radiocarbon dating (Awe, 1992), correspond with a preceramic occupation at site based on the presence of chert debitage but no ceramics. Subsequent excavations conducted at Str. B4 (Ishihara-Brito and Awe, 2013; Garber and Awe, 2008) and Plaza B (Horn, 2015; Peniche May 2016) have recovered deposits containing both chert and Cunil ceramic artifacts. Additionally, our chronological model for Cahal Pech indicates that the first directly Cunil phase construction episode at the site (Str. B4/1st) occurred between 1195 and 985 cal BCE, when the area was cleared for the placement of a tamped marl floor for a small domestic structure (Awe, 1992). We suggest that an increase in the summed probability distribution for Cahal Pech around 1000 cal BCE likely corresponds to increasing levels of construction activity within the site core, rather than the initial settlement of the site, suggesting that people were already inhabiting this part of the site prior to 1000 cal BCE. Additional radiocarbon dating work from early contexts at Cahal Pech may help to resolve this issue, however, the processes of transition to sedentism and adoption of ceramic technology at this site and others elsewhere in the Maya lowlands was likely a relatively gradual process, occurring over more than 200 years.

The earliest Maya communities in Belize settled in areas with abundant resources in alluvial valleys or on the margins *bajos*, natural depression that hold shallow lakes and perennial wetlands (Beach et al., 2002; Dunning et al., 2002). Initial settlement at Cahal Pech between 1200 and 1000 cal BCE coincides with a multi-century drying trend characterized by smaller punctuated droughts of varying intensities recorded in paleoclimate proxy records from the southern Maya lowlands (Akers et al., 2016; Hodell et al., 1995; Medina-Elizalde et al., 2016; Wahl et al., 2014). Population levels in the Belize Valley were likely very low at this time, however, offering little competition in the resource-rich alluvial valley so that climatic variability had relatively low impact upon initial settlement. In Northern Belize, archaeologists working at the site of Cuello have documented the construction of small, low domestic platforms associated with the first ceramics (Swasey ceramic complex, 1100-900 cal BCE) in the region (Hammond, 2009; Kosakowsky, 1987). This site is located near *bajo* wetlands that extend across much of Northern Belize, suggesting a similar timing in the adoption of sedentism in this resource-rich region of the lowlands (Dunning et al., 1998; Hammond, 2009). While current archaeological data provide limited evidence for institutionalized social inequality between 1200 and 1000 cal BCE in the lowlands, the presence of non-local goods (e.g., jade, flake obsidian, marine shell) and presence of vessels decorated with pan-Mesoamerican iconography within early levels link Cahal Pech and other Belize sites into broader regional economic networks (Awe, 1992; Awe and Healy, 1994; Garber et al., 2004; Hammond, 2009; Horn, 2015; Peniche May 2016).

The climate conditions beginning in the Middle Preclassic remained relatively dry, though high levels of climatic volatility are present in paleoclimate proxy records between ~1000 and 500 cal BCE. While the Itzamna (Río Secreto) speleothem record shows six major droughts, these intervals are bracketed by several wet intervals lasting several decades (Medina-Elizalde et al., 2016). Similar patterns are present in the Macal Chasm record (Akers et al., 2016). Alternating wet and dry conditions likely provided a challenging context for early agrarian communities, however, the summed probability distribution for Cahal Pech increases dramatically during this time. These data suggest that the site's inhabitants were able likely able adapt to climatic variability, perhaps because of the local environment. Regional summed probability distributions for the Belize Valley, Northern Belize, and Pasión region, on the other hand, show alternating peaks and valleys characteristic of societal cycling. While wet phases likely allowed Maya farmers to begin exploit productive soils and seasonal wetlands for more intensive maize agriculture (Dunning et al., 1998, 2002; Luzzadder-Beach et al., 2012), providing a context for the growth of many small polities, dry phases may have influenced periods of social instability. This pattern may be especially pronounced in the Pasión region, where the local terrain is characterized by considerable fluctuations in seasonal water levels (Dunning et al., 1998). Inomata and colleagues (2015) have argued, based on a lack of residential architecture associated with early contexts (~1000-900 cal BCE), that the earliest inhabitants of Pasión site of Ceibal may have been residentially mobile or semi-mobile. The Bayesian chronology for Ceibal and the nearby minor center of Caobal indicates the presence of the first formal public architecture by 950 cal BCE, however, which included an E-Group architectural assemblage with buildings that likely served as a stage for communal ritual performances (Inomata et al., 2013, 2015, 2017; see also Doyle, 2017). While the summed probability density of ^{14}C dates for Ceibal is affected by steep areas of the calibration curve during the Middle Preclassic, a large number of radiocarbon dates coupled with archaeological evidence indicate that monumental building in the civic-ceremonial core of the site peaked after 800 cal BCE (Inomata et al., 2017). Wet periods may have provided a more suitable for groups to aggregate more permanently and construct larger architecture at the site.

The radiocarbon chronology for Plaza B in the Cahal Pech site core documents a similar shift from a focus on domestic to primarily public architecture slightly later after 700-500 cal BCE (late facet Kanluk ceramic phase), though the chronology is less clear for this part of the site's history due to the impacts of the Hallstat Plateau in the radiocarbon calibration curve that result in large calibrated date ranges. The period just before 500 BCE, however, coincides with the onset of onset of humid conditions in the Río Secreto speleothem record, characterized by a progressive increase in precipitation beginning around 500 cal BCE (Medina-Elizalde et al., 2016:96–97). Increased rainfall levels are also reflected in the higher resolution Cariaco Basin and Macal Chasm paleoclimate records beginning around 500 cal BCE. During this time (late Kanluk ceramic phase), there is increased construction in Plaza B compared to earlier time periods (Peniche May 2013, 2014, 2016). Several large circular and keyhole-shaped platforms ~1–2 m high were constructed in Plaza B during the interval from 700 to 500 cal BCE. Similar buildings have been documented for Middle Preclassic contexts at the Tolok and Zotz settlement groups in the Cahal Pech periphery (Aimers et al., 2000; Awe, 1992; Powis, 1996:174), and have also been reported in a small number of other sites in the Belize Valley (Barton Ramie, Willey et al., 1965), Northern Belize (Altun Ha, Pendergast, 1982; Colha, Potter et al., 1984; Sullivan, 1991; Cuello, Hammond, 2009; K'axob, McAnany, 1995), the Petén (Uaxactun, Hendon, 1991), and some parts of the northern lowlands (Becan, Ball and Andrews, 1978; Xamán Susulá, Peniche May et al., 2009). These Middle Preclassic structures are often associated with high-status burials or dedicatory caches, and some scholars have argued that they functioned as ancestral shrines for higher status households (Aimers et al., 2000; Hendon, 1991, 2000). While these structures were relatively modest compared to later Classic period temple buildings that dominated the Cahal Pech site core, their construction nonetheless required the organization of labor and investment of resources beyond the level of the household. Additionally, these buildings are also associated with larger residential architecture, perhaps suggestions that higher-status groups were controlling these spaces (Peniche May 2016).

At the beginning of the Late Preclassic period (400-300 cal BCE), rapid growth of major civic-ceremonial centers occurred across most parts of the southern lowlands during the onset of the wettest phase of the Preclassic period recorded in regional paleoclimate records (Akers et al., 2016; Haug et al., 2003; Medina-Elizalde et al., 2016; Wahl et al., 2014). While large political centers of Nakbe and El Mirador dominated the central Petén, other regions also experienced considerable demographic and political expansion. Settlement data from Cahal Pech in the Belize Valley document a substantial increase in population beginning in the Late Preclassic. Radiocarbon dates parallel this trend, with the construction of larger-scale residential and nonresidential construction in at least five house groups (Burns Avenue Group, Cas Pek, Tolok, Tzutziiy K'in Group, and Zopilote Group) in the Cahal Pech periphery after ~350 cal BCE (Awe, 1992:207; Ebert et al., 2016a; Iannone, 1996; Powis, 1996; Willey and Bullard, 1956). Settlement expansion in the periphery was concurrent with large-scale construction of monumental architecture in the Cahal Pech site core at both Plazas A and B (Awe, 1992; Healy et al., 2004a). The cobbled platforms associated with Plaza B/12th (765-535 cal BCE), the last dated Middle Preclassic constructions for Plaza B, were completely covered by five successive plastered plaza floors (Peniche May 2016) associated with two buildings located beneath Str. B5 (Peniche May and Beardall, 2015). A single radiocarbon date (105 cal BCE-cal 15 CE) below Floor 8 indicates that this construction activity was taking place throughout the Late Preclassic. This event occurred just after one of the most severe dry periods recorded for the southern lowlands (Akers et al., 2016), with the return of wet conditions possibly encouraging renewed activity at the site core. Other Belize Valley sites, including Baking Pot (Hoggarth et al., 2014), Chan (Kosakowsky, 2012), Lower Barton Creek (Kollias, 2016), and the Vaca Plateau site of Caracol (Chase and Chase, 1987, 2006) also experienced intensified architectural construction programs. In Northern Belize, over a dozen medium and large regional centers with monumental architecture also emerged during the Late Preclassic including Cerros, K'axob, Lamanai, Nohmul, San Estevan, and Santa Rita (Chase and Chase, 1987; Pyburn, 1989; McAnany and Lopez-Varela, 1999; Rosenswig and Kennett, 2008).

One of the most prolonged and severe droughts in recorded paleoclimate proxies from throughout the Maya lowlands occurred at the end of the Late Preclassic period (cal 100–300 CE; Akers et al., 2016; Curtis et al., 1996; Hodell et al., 2005; Kennett et al., 2012; Medina-Elizalde et al., 2016). Changes in the frequency of building activity evident in summed probability distributions of ^{14}C dates suggest regionally distinct responses to drought within the southern lowlands. Although no radiocarbon dates with clearly reported contexts are available for sites in the Mirador Basin, settlement data indicate the almost complete abandonment of Nakbe and Mirador in addition to massive depopulation in the area after cal 200 CE (Beach et al., 2015; Dunning et al., 2014; Hansen et al., 2008; Rice and Rice, 1990). Drought may have significantly impacted seasonal water availability in this part of the lowlands, where perennial surface water is scarce across the karstic landscape (Kuil et al., 2016; Wahl et al., 2006, 2014) and artificial reservoirs were necessary to support concentrated populations (Dunning et al., 1998). The sites of San Bartolo (Saturno et al., 2006) and Cival (Estrada-Belli, 2006) were also largely devoid of inhabitants by cal 150 CE, though the connection to drought has not been directly investigated at these sites. Summed probability distributions of radiocarbon dates and archaeological data document massive expansion and political centralization at Tikal, Calakmul, and other regional centers (e.g., Cival and Holmul, Estrada-Belli, 2006) at the beginning of the Early Classic (~cal 200–300 CE), corresponding with a decline of authority at these earlier centers of power and socio-political influence (Hansen, 2005; also Martin and Grube, 2008). Population decline in the Pasión region at the end of the Late Preclassic at Ceibal and neighboring sites has also been documented based on declining frequencies of ceramic artifacts and evidence for construction activity beginning around 75 cal BCE, reaching a low point between cal 125–175 CE (Inomata et al., 2017), coincident with acute Late Preclassic conditions. These trends are mirrored in the summed probability distributions for the Pasión region, coincident with the Late Preclassic drought, suggesting that dry climate conditions may have played a role in construction activity at Ceibal and other sites in the region.

Political reorganization possibly influenced by drought conditions is evident elsewhere in the Maya lowlands, where more varied responses are evident in the record. A declining probability distribution of radiocarbon dates from Northern Belize may reflect local socio-political instability during the Late Preclassic, when there is evidence at multiple sites for inter-polity conflict (Estrada-Belli, 2011; Rosenswig and Kennett, 2008). At the large port city of Cerros, a large ditch system, possibly built for defensive purposes (Scarborough, 1983, 1991:183) and stucco facades displaying "jaguar war complex" imagery (Freidel, 1986:101; Freidel and Schele, 1988) appear between 200 and 50 cal BCE. The summed probability distribution for the available Cerros radiocarbon dates also shows a sharp decline after cal 200 CE, reflecting the political decline of the site. Coastal populations may have contracted around sites located in more resource rich riparian zones, such as Lamanai and Nohmul, which resumed growth during the Early Classic period (Pyburn, 1989:194). In southern Belize, summed probability of radiocarbon dates from the site of Uxbenká provides strong evidence for the rapid development of this polity during the end of the Late Preclassic (Aquino et al., 2013; Culleton et al., 2012; Prufer et al., 2011). While the YOK-I speleothem record, located 1.5 km from the Uxbenká site core, documents severe dry conditions at the end of the Late Preclassic (Kennett et al., 2012), relatively high levels of rainfall compared to other locations in the Maya lowland may have allowed the local community to flourish during a period of climatic volatility.

Radiocarbon data provide evidence that Cahal Pech and other sites in the Belize Valley may have also been resilient in the face of severe Late Preclassic drought conditions compared to the Mirador centers and sites in Northern Belize and the Pasión region. While relatively little Late Preclassic and Early Classic materials were recovered from the Plaza B and Str. B4 excavations, radiocarbon data document continual growth of settlement groups within the Cahal Pech hinterland through the Early Classic. Initial construction phases of mounds in several house groups occurred at the end of the Late Preclassic, also reflecting population growth at the site.

Excavations from other locations indicate that the focus of construction shifted to other locations within the Cahal Pech civic-ceremonial core during the Late Preclassic and into the Early Classic. Several structures within Plaza A were remodeled into monumental building; Plazas C, D, F, and G grew substantially through the construction of new temple and palatial buildings; and the first phase of the eastern ball court was erected (Awe, 1992; Awe and Helmke, 2005: Table 1). Str. B1, the central pyramid building of a large eastern triadic group in Plaza B is associated with some of the most elaborate royal burials at the site, became the focal point of the site core by the Late Preclassic period (Awe et al., 2017). Radiocarbon dating of remains of multiple individuals from Burial 7 found within Str. B1 indicates that the earliest royal tomb was constructed by at least cal 140–395 CE (Novotny, 2015; see also Awe and Zender, 2016). Similar large-scale monumental groups with elite burials or caches have been dated to the Late Preclassic at the Belize Valley sites of Chan (Robin, 2012), Pacbitun (Healy et al., 2004b), and Blackman Eddy (Garber et al., 2004). Intensified construction programs and increased population growth indicate that the inhabitants of Cahal Pech and other Belize Valley sites flourished in spite of drought conditions at the end of the Late Preclassic. Access to reliable surface water in the Belize Valley from the Belize, Macal, and Mopan Rivers, in addition to abundant fertile agricultural land in the alluvial flood plain may have provided an important foundation for increased economic and political activity and allowed Cahal Pech to be more resilient in the face of climate change during this time. Additional dating work is required to understand the timing of monumental growth at Cahal Pech and elsewhere in the Belize Valley during the transition from the Late Preclassic to the Early Classic period.

6. Conclusions

Multiple independent polities emerged rapidly in the Maya lowlands after the initial establishment of sedentary agricultural villages and the adoption of ceramic technology between 1200 and 1000 cal BCE. Over the course of the following millennia, lowland Maya populations expanded across the landscape, and numerous large centralized polities with hierarchical political organization developed. Radiocarbon dating and Bayesian chronological models from site core and residential contexts at Cahal Pech offer a new way to explore human-environment interactions in the Belize Valley. The Cahal Pech chronology can be compared to radiocarbon dates from other sites across the Maya lowlands where ceramic-based chronologies are often difficult to correlate or are contentious (e.g., Inomata, 2017; Lohse, 2010). The chronology modeled here for Cahal Pech, one of the earliest known Preclassic Maya villages with ceramics, helps to clarify the timing of changes that allowed the site to become a large socio-political center by the Late Preclassic. After initial settlement of the site around 1200/1100 cal BCE, construction activities focused on the expansion of domestic architecture. During the Middle Preclassic, beginning around 800-700 cal BCE, the first public architecture and larger residential structures appear at the site, suggesting the development of a centralized hierarchy within the community. The pace of monumental construction slowed in the site core at the end of the Middle Preclassic, but summed probability distributions of radiocarbon dates corresponding to building activities at the site show that populations were growing at a steady rate into the Late Preclassic and Early Classic when the first ruling lineage was firmly in place.

Increasing emphasis in Maya archaeology has been placed on examining the timing and variability of Preclassic period cultural changes as responses to changing environmental conditions (Beach et al., 2015; Chase and Scarborough, 2014; Iannone, 2014; Kennett et al., 2012; Kennett and Beach, 2013; Kennett and Marwan, 2015; Luzzadder-Beach et al., 2012). Research on later Classic Maya society has documented that the formation and consolidation of centralized regional polities was favored during stable climatic regimes between cal 400–700 CE (Kennett et al., 2012; Medina-Elizalde et al., 2010). Our analysis of the available data from the Preclassic suggests a more complex picture. Based on the summed probability distributions of radiocarbon dated building episodes and archaeological evidence, we identified contrasting patterns of socio-political change in relationship to fluctuating climatic conditions across the lowlands. During the Early Preclassic, low population levels in the Belize Valley and Northern Belize, as well as diverse subsistence strategies focused on local aquatic and riparian resources, may have allowed small communities to adapt to alternating wet and dry periods (Dunning et al., 2014). The impacts of prolonged multi-decadal and century-long droughts likely became more pronounced in the Late Preclassic as population levels reached their peaks and regional polities became focal points in complex social, political, and economic systems. The multi-century drought occurring at the end of the Late Preclassic is one of the most severe drying events recorded in the region during the last 4000 years. The socio-political and population decline in many parts of the southern lowlands in the face of the drought, however, differed from the Terminal Classic droughts in that it was followed by the development of new, resilient political centers throughout the lowlands in the Early Classic that flourished in some cases for over six to seven centuries. While drought was one possible mechanism stimulating culture change in the Maya region, the results of this research highlights the complex and non-linear relationship between climate change and socio-political dynamics. Rather, fluctuating social and natural conditions favored the emergence of multiple adaptive pathways for complex societies. Future research should focus on additional radiocarbon dating efforts from Preclassic period sites across the Maya lowlands to more precisely document the timing and tempo of responses to long-term climate change and its impact on the complexity of coupled socio-natural systems.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2017.08.020.

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