ANTHROPOLOGY

Origins of Mesoamerican astronomy and calendar: Evidence from the Olmec and Maya regions

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Archaeoastronomical studies have demonstrated that the important civic and ceremonial buildings in Mesoamerica were largely oriented to sunrises or sunsets on specific dates, but the origin and spread of orientation practices were not clear. Using aerial laser scanning (lidar) data, we analyzed orientations of a large number of ceremonial complexes in the area along the southern Gulf Coast, including many recently identified Formative sites dating to 1100 BCE to 250 CE. The distribution pattern of dates marked by solar alignments indicates their subsistence-related ritual significance. The orientations of complexes built between 1100 and 750 BCE, in particular, represent the earliest evidence of the use of the 260-day calendar, centuries earlier than its previously known use in textual records.

INTRODUCTION

Considering the antiquity of astronomy and its importance in ancient civilizations, it is hardly unexpected that "perhaps more often than we have yet recognized, the sky provides the cues to spatial order on the terrestrial plane" [(*1*), p. 3]. Since the sky provides basic references for orientation in space and time, the observation of celestial regularities resulted in practically useful knowledge. However, the seemingly perfect and divine order observed in the sky also gave rise to a variety of ideas explaining the role of celestial bodies in the cosmic order and their influence on earthly affairs. Both kinds of concepts, which, in any social group, are intertwined and integrated in a relatively coherent worldview, had an important role in landscape formation and conceptualization and were frequently expressed in the astronomically based alignments found in ancient architecture and urban patterns. Studies of this aspect of spatial order can thus provide important insights into extinct cognitive worlds, which are difficult or impossible to grasp from other data sources.

While the directions materialized in a cultural landscape may derive from a variety of orientation motives, such as geomorphology, climate, defensive concerns, or geomancy, systematic archaeoastronomical research in Mesoamerica has shown that the architectural orientations exhibit a nonrandom distribution that can only be explained with the use of rising and setting points of celestial bodies as reference objects. Most orientations refer to sunrises and sunsets on certain dates. The intervening intervals tend to be multiples of 13 and 20 days, indicating a relationship with the Mesoamerican calendars, particularly with the 260-day cycle, in which a series of 20 day signs intermeshed with numbers from 1 to 13 (it should be noted that any solar, except a solstitial, orientation matches two sunrise and two sunset dates, and each pair of dates delimits two complementary intervals whose sum is equal to the length of the tropical year). Astronomical observations were necessary because there was no intercalation system for maintaining a permanent correlation between the calendrical (365-day) and the slightly longer tropical year. The orientations, marking dates separated by multiples of the elementary calendrical periods, most likely enabled horizon-based observational calendars that facilitated a proper scheduling of seasonal activities and corresponding rituals. By combining the formal calendar and astronomical observations, it was relatively easy to predict the relevant dates (the dates separated by multiples of 13/20 days had the same number/sign of the 260-day calendrical cycle), even when direct observations on those days were impeded by cloudy weather. Since the rituals had to be prepared ahead of time, this anticipatory aspect of observational calendars must have been of foremost importance. However, since the simple objective of timekeeping through solar observations could have been achieved without monumental constructions, the significance of orientations needs to be understood within a broader cultural context. The repeated occurrence of specific directions exhibited by civic and ceremonial architecture indicates that the appropriately oriented buildings had an important place in the worldview and cosmologically substantiated political ideology (*2*–*6*).

The prevalence of the 260-day calendar across Mesoamerica has led various scholars to suspect that Gulf Coast Olmec culture played an important role in its development and spread and that its origins date to the era of the Middle Formative Olmec center of La Venta between 800 and 400 BCE or even earlier to the apogee of the Early Formative center of San Lorenzo between 1400 and 1100 BCE (*7*). Reliable evidence of its origin, however, has been lacking. Before our study, the earliest unequivocal epigraphic evidence of the 260-day calendar was a 7–deer day sign found in Late Formative mural paintings at the central lowland Maya site of San Bartolo, Guatemala, dated to 300 to 200 BCE (*8*). Scholars have proposed earlier evidence of calendar use, but its validity has been questioned. A ceramic cylinder seal found at the site of San Andrés located near La Venta had a design, which the excavators argued was a day sign of the 260-day calendar (*9*). The object appears to date between 700 and 500 BCE, but Stuart *et al.* (*8*) suggest that it may be an iconographic element, not a day sign. Monument 3 of San José Mogote located in the Oaxaca Valley has a more likely 260-day calendar day sign (*10*). Nonetheless, its originally suggested date of 600 to 500 BCE has been disputed, and it may date between 100 BCE and 200 CE instead (*11*, *12*). Architectural orientations have been expected to provide early evidence of calendar and astronomical

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observations, but previous studies included relatively few structures predating the Late Formative period (~400 BCE to 200 CE). Here, we present the results of analyses of a large number of orientations in southern Mesoamerica, which constitute the earliest evidence of the use of the Mesoamerican 260-day calendar dating to 1100 to 750 BCE. In general, our alignment data, which reflect the attention paid to both the Sun's annual motion and other celestial events, including Venus and lunar phenomena and their regularities, reveal that the observations leading to the sophisticated astronomical knowledge of the Classic and Postclassic periods were underway nearly a millennium before it was first attested in epigraphic records.

Dataset

Recent lidar-based archaeological research in an area of 84,516 km^2 connecting the Olmec core zone with the western Maya Lowlands identified 33,935 architectural complexes and mound groups. Among them, 478 were standardized complexes dating to the Formative period. They included four major types: Middle Formative Usumacinta (MFU), Veracruz Ceremonial (VC), Middle Formative Chiapas (MFC), and Middle Formative Gulf (MFG) patterns (*13*). An MFU complex consists of an extensive rectangular formation defined by a series of mounds along its edges (Fig. 1). At its center is a so-called E-Group assemblage, which is usually made of a western pyramid and an eastern elongated platform flanking a plaza. E-Groups are found at many Formative centers across the Maya lowlands, although outside our study region mostly without the rectangular formation of the MFU, and likely served as the foci of community ritual (*14*).

The largest of the MFU sites in our study area was Aguada Fénix with its main artificial plateau measuring 1400 m in length, 400 m in width, and up to 15 m in height. Excavation results suggest that a large portion of the plateau was constructed between 1100 and 750 BCE, making it the earliest and most voluminous structure known so far in the Maya area (*15*). Two other excavated MFU complexes, La Carmelita and Buenavista, date to 900 to 750 BCE. Excavation data suggest that the original versions of these complexes already had formal rectangular formations, and their orientations were maintained through a series of renovations. In addition, some MFU complexes, including Aguada Fénix, Buenavista, and El Macabil, were laid out according to large-scale grid-like patterns that extended beyond the rectangular complexes. These patterns indicate that the orientations and forms of those complexes were conceived before their construction began (texts S1 and S5). Some MFU complexes, including Aguada Fénix, Buenavista, El Macabil, and El Cacho, have 20 edge platforms, which probably represent the base unit of the Mesoamerican calendars (Fig. 1). VC complexes are found mostly in southern Veracruz. Their plans are similar to those of the MFU pattern, but they often have continuous linear mounds along the edges and, in some cases, lack an E-Group. Surface collection data obtained by other archaeologists suggest that VC complexes are contemporaneous with MFUs or slightly earlier (*13*).

MFC complexes were previously identified by Lowe, McDonald, and Clark on the southern Gulf Coast and along the Grijalva River in central Chiapas (*16*–*19*). Their arrangements with an E-Group are similar to MFUs but without clear rectangular forms and often with taller pyramids and mounds. La Venta was classified as an MFC complex by those scholars, but the tight placements of its edge platforms in linear formations, as opposed to the more dispersed patterns of other MFCs, resemble those of MFU complexes. Thus, we defined the MFG pattern, including La Venta and similar complexes, as a subtype of the MFC pattern (*13*). A prototype of MFC and MFG complexes may be found at the Pacific Coast site of Ojo de Agua, which dates to 1200 to 1000 BCE (*20*). Nonetheless, most MFC and MFG complexes in the study area, including La Venta, probably date to 800 to 400 BCE (*19*), and a few were built later. We also defined the types of Rectangle and Square, which likely were contemporaneous with MFUs or MFCs. A Rectangle has a rectangular form similar to that of the MFU pattern but lacks a clearly defined E-Group. A Square is characterized by lineal mounds surrounding a square space.

After the apparent abandonment of these formal complexes, a number of later sites, typically with tall pyramids and numerous residential mounds, were established. We suspect that many of them

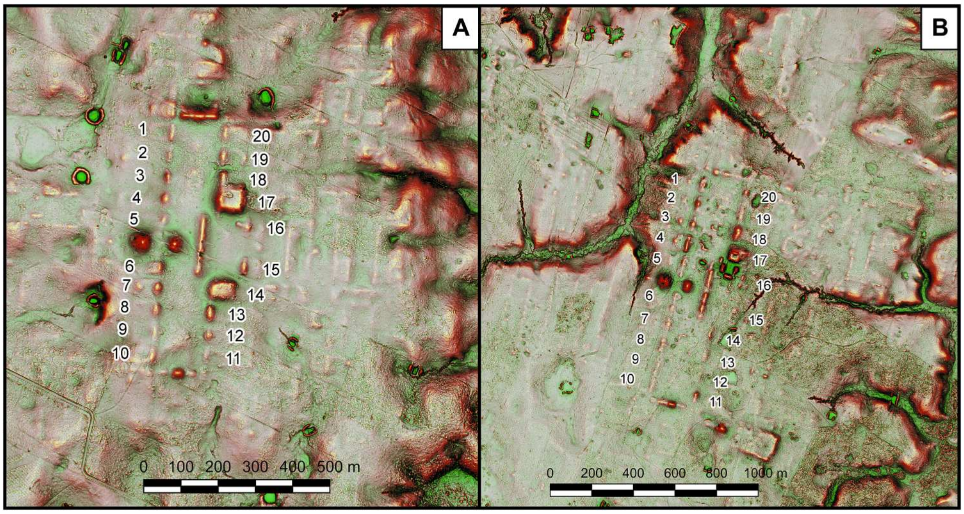

Fig. 1. Lidar-based images showing MFU complexes with an E-Group assemblage, 20 edge platforms, and grid-like patterns. (**A**) Buenavista. (**B**) El Macabil. Red Relief Image Map visualization enhances the visibility of subtle grid features.

date to the Late Classic period (600 to 1000 CE). They commonly exhibit diverse configurations, but Classic Veracruz compounds (also called Long-Plaza Plan, Villa Alta Quadripartite Arrangement, or Tipo 4) found in southern Veracruz have a standardized plan, consisting of two parallel elongated structures flanking a plaza and a pyramid on one or two shorter edges of the plaza (*21*–*23*).

A large number of sites with clearly visible layouts on the lidar-derived relief model allowed us to acquire alignment data on 415 Formative and Classic complexes (Fig. 2). This large dataset presents an important advantage for the study of architectural orientations. In the absence of independent evidence suggesting an astronomical rationale (iconography, written records, etc.), convincing astronomical interpretations can only be proposed with a sufficient number of examples. Our data also allow us to examine chronological trends in architectural orientations from the Formative to the Classic. In several cases, only north-south or east-west alignments could be measured (N-S, *n* = 365; E-W, *n* = 344; table S1). Depending on the resolution of lidar data from different sources (*13*, *15*), possible errors were estimated and assigned to each alignment azimuth, and the corresponding declinations were calculated. For declinations within the solar span, the corresponding dates in relevant periods and the intervening intervals were also determined. To assess the degree of intentionality of correspondences of alignments and their astronomical correlates, these data were plotted and analyzed using kernel density estimation (KDE; see Materials and Methods).

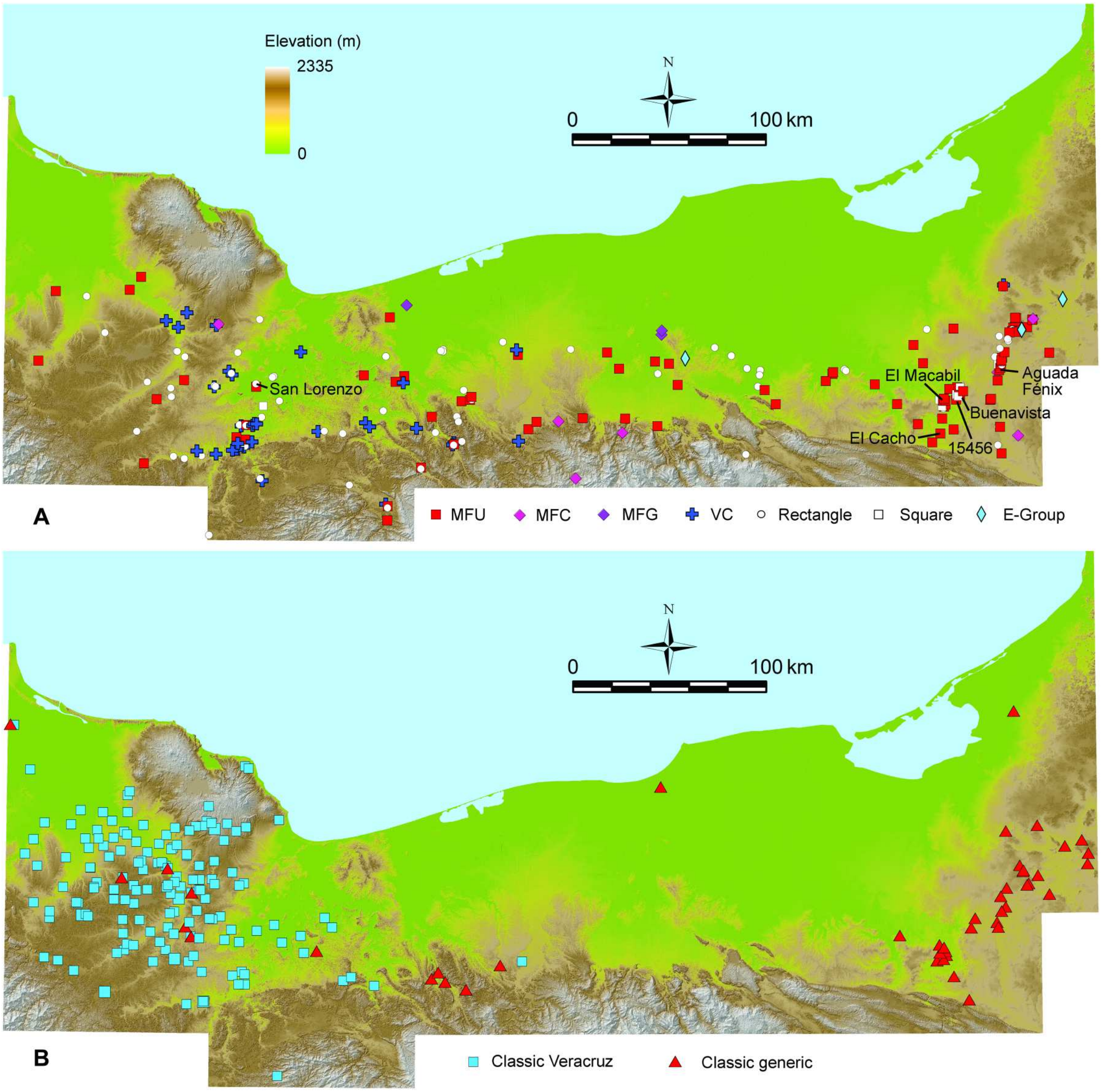

Fig. 2. Map of the area with the location of sites included in the study. (**A**) Formative period sites. (**B**) Classic period sites. The symbols for E-Groups only show standalone complexes; many more E-Groups are integrated in larger complexes (MFUs, etc.). While Classic Veracruz compounds have a standardized plan, other sites from that period have diverse configurations and are designated as Classic generic.

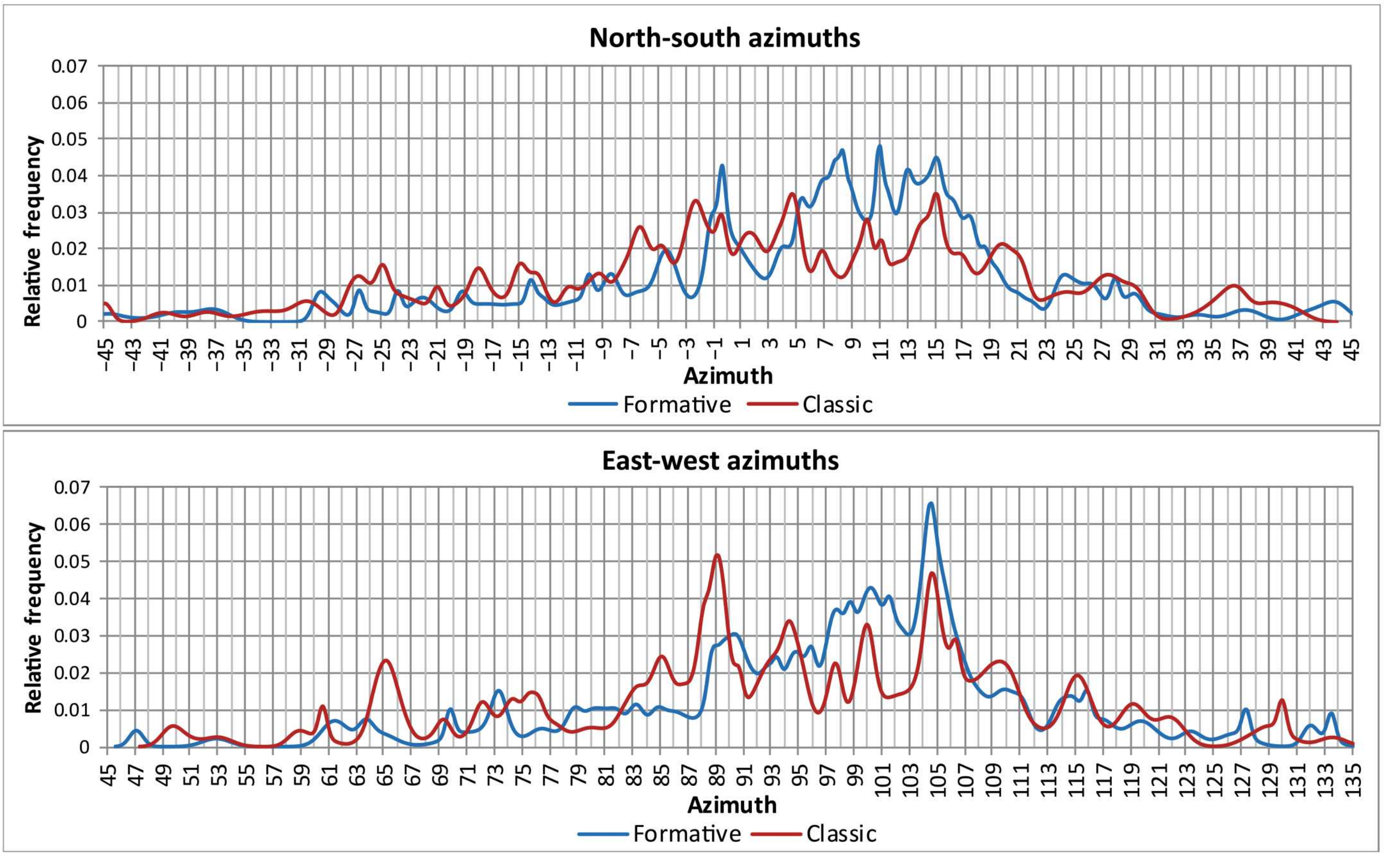

Fig. 3. Relative frequency distributions of azimuths by period.

RESULTS

The nonuniform distribution of azimuths (Fig. 3) points to an astronomical rationale. The more pronounced clustering of E-W than of N-S azimuths and the lack of clear correspondences of alignments with bright stars to the north and south indicate that astronomical events were targeted mostly by E-W alignments (for details, see Materials and Methods). A substantial portion (~89%) of the E-W azimuths falls within the angle of solar movement along the horizon (between ~65°/245° and 115°/295°), suggesting that the orientations largely refer to sunrises or sunsets on certain dates (with a random distribution, only ~57% of E-W azimuths would have expectedly been within that angle). Consequently, although the possibility that some of the N-S alignments had stellar referents cannot be discarded, the following analysis focuses on the 344 E-W alignments that we have determined (45° ≤ azimuth ≤ 135°).

The distributions of alignment data by structural type (figs. S1 to S3) show that, while there was a shift in orientation trends from the Formative to the Classic period, particular building types do not correlate preferentially with specific orientations. Therefore, the KDE graphs show relative frequency distributions of relevant data plotted separately for all Formative and Classic constructions (Figs. 3 to 5). Since certain celestial events were marked on either the eastern or the western horizon and because of other factors (see Materials and Methods), the targeted and unintended values often blend in these graphs. Despite these limitations of the method, the clustering of data (declinations, dates, and intervals) indicates the existence of a few prominent orientation groups, for which an explanation other than astronomical is hardly conceivable. The groups that can be related to the Sun (declinations between ~24° and −24°) are particularly clear and labeled with numbers in Figs. 4 and 5.

The most widespread orientation group in the Formative, indicating the underlying calendrical principles, was group 1, corresponding to sunrises on February 11 and October 29, separated by 260 days (eastern interval peaks at 105.13/260.12 days; Fig. 5). This was the most pervasive orientation group in later Lowland Maya architecture as well and very common also elsewhere in Mesoamerica (*4*, *5*). While the sunset dates corresponding to this orientation group (around 17 April and 27 August) and the intervening intervals (around 112/253 days) have no conceivable significance, the sunrises separated by 260 days occurred on the same dates of the ritual calendrical cycle, a fact that supports the eastern directionality of these orientations and represents the most obvious reason for their popularity. The great majority of these orientations in our sample is embedded in complexes most likely dating to 1100 to 750 BCE, if not earlier, and thus represents the earliest evidence of the 260-day calendrical cycle. The orientations of this group, skewed south of east, marked 11 February and 29 October on the eastern horizon (Fig. 6A); however, some structures, deviated counterclockwise from cardinal directions, recorded the same dates on the western horizon (table S1).

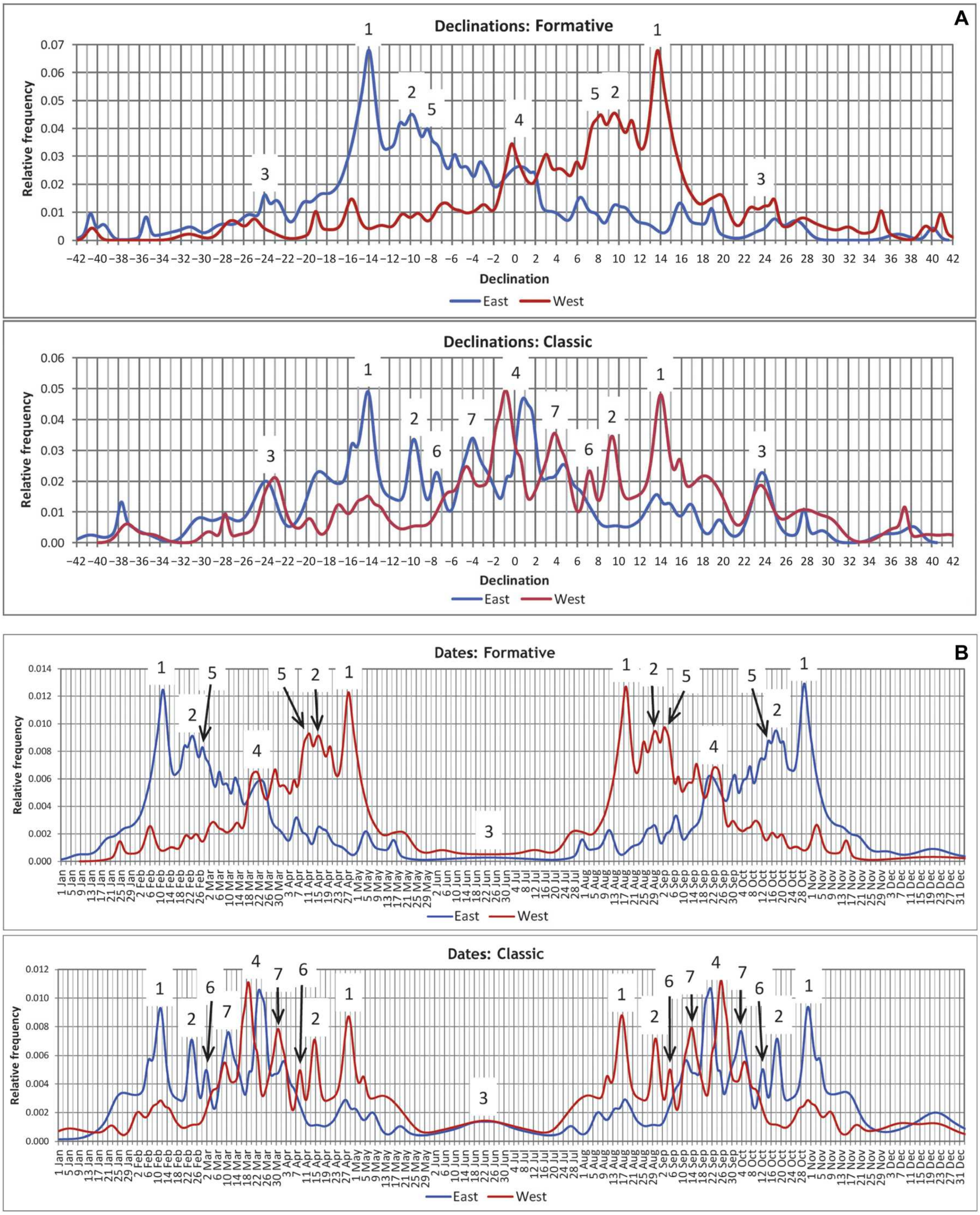

Fig. 4. Relative frequency distribution of declinations and dates by period. **(A)** Declinations. **(B)** Dates. Note that any solar (except a solstitial) alignment corresponds to two sunrise and two sunset dates. The most evident orientation groups are designated by numbers.

It seems significant that the alignment of two central mounds of MFU minor 22305 (azimuth = 104.27° ± 0.5°; table S1), prolonged eastward, passes almost exactly over a structure about 380 m away. If this structure is contemporary and actually indicates the intended alignment (azimuth = 104.64°, horizon altitude = 0.54°, and declination = −13.88°), it would have accurately recorded sunrises on 11 February and 29 October, separated by 260 days (Fig. 7). The astronomically based intentionality of this spatial relationship is supported by similar situations at several sites in the Maya Lowlands, where a building is oriented to both the Sun's position on significant dates and a structure placed in the same direction (*4*, *5*).

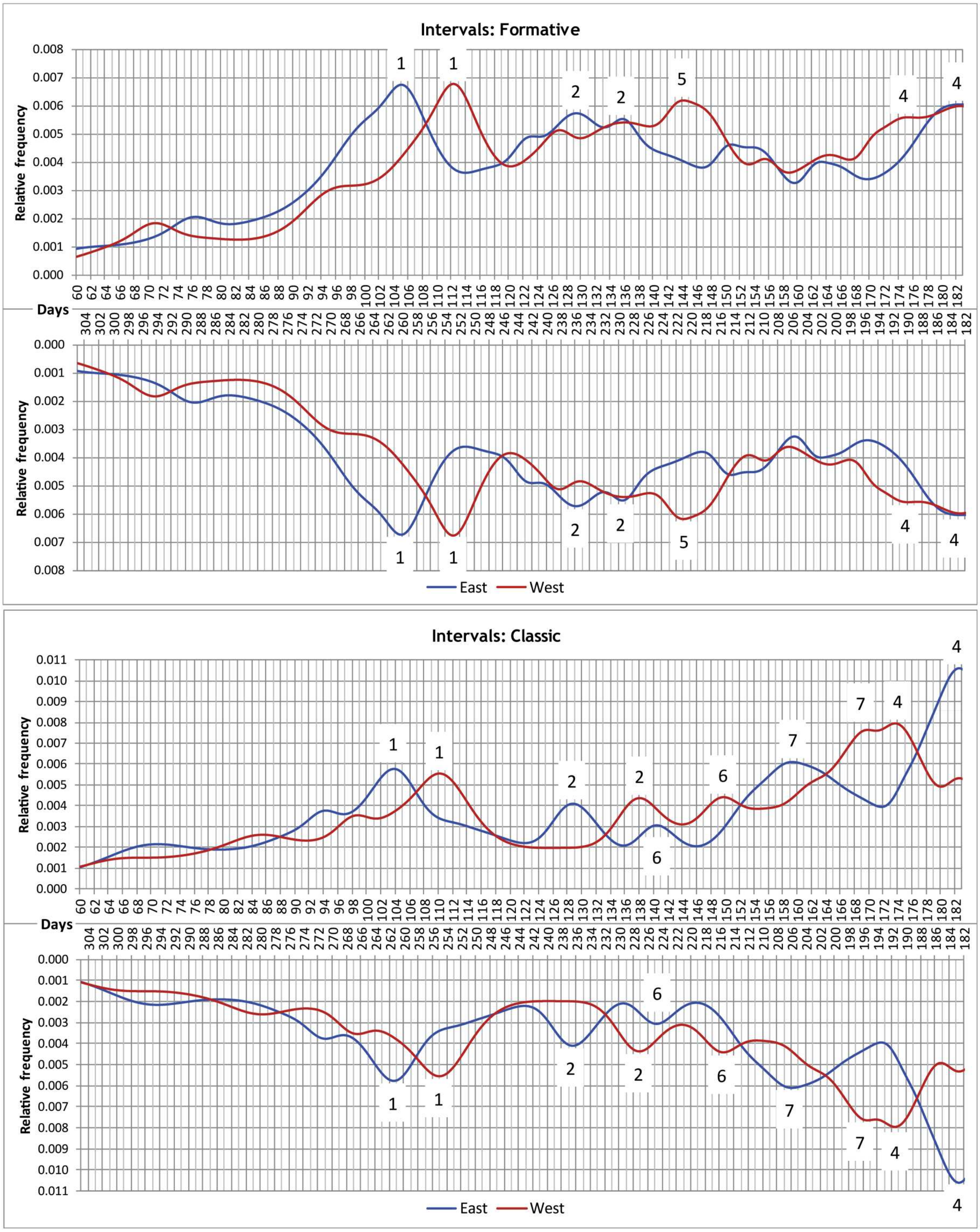

Fig. 5. Relative frequency distribution of intervals by period. The distributions of short/long intervals delimited by pairs of sunrise and sunset dates (cf. Fig. 4) are plotted in the upper/lower part of each graph. The interval peaks corresponding to the most evident orientation groups are designated by numbers.

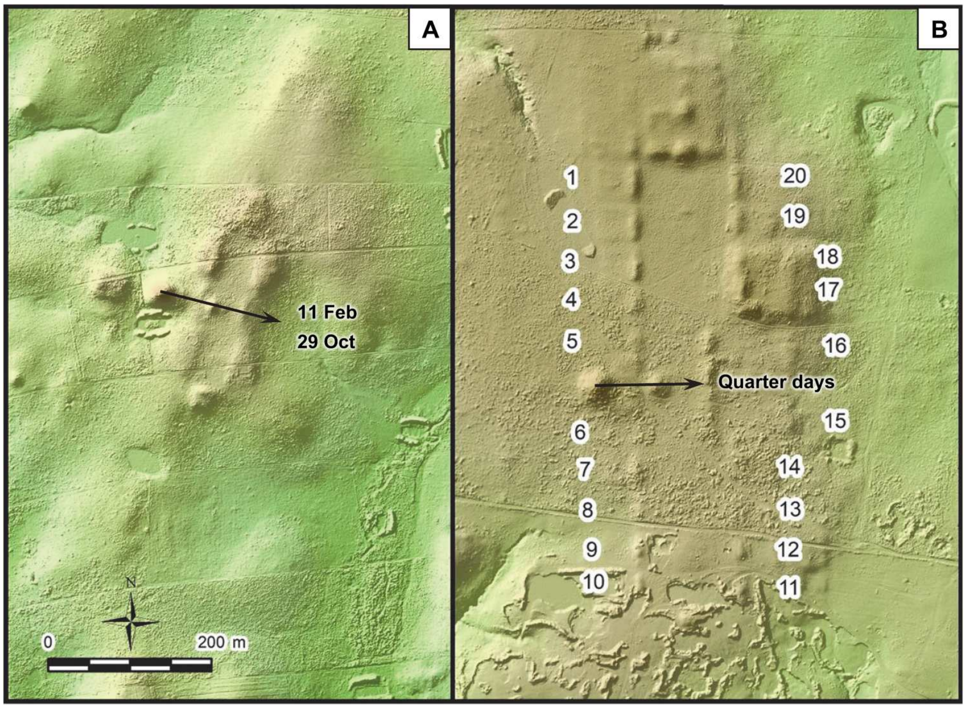

Fig. 6. Lidar-based images showing examples of solar orientations pertaining to group 1 (260-day interval) and group 4 (quarter-day sunrises). Both images are on the same scale. (**A**) MFU and E-Group at site 15456. (**B**) MFU and E-Group at El Cacho (site 14599). The 20 edge platforms at El Cacho (and other sites: Figs. 1 and 8) likely represent the base unit of the Mesoamerican calendar. The southern part of El Cacho is damaged by the modern extraction of construction material.

Other orientation groups also reflect the use of the 260-day calendar. Group 2, also frequent in the Formative, matches sunrises on 24 February and 17 October, separated by 130 days, or half of the 260-day count (Figs. 4 and 5; again, the intervals separating sunset dates marked by the same group, around 136/229 days, do not appear significant). A prominent example is Aguada Fénix (Fig. 8B) dated to 1100 to 750 BCE (*15*). This group was also prominent elsewhere in the Maya Lowlands, as was group 5, which likely marked another multiple of 13 days, either 143 or 221 days, delimited by sunsets on 11 April and 1 or 2 September. The 143-day interval was the more likely target because it was marked by a number of central lowland E-Groups of the Formative period (*24*).

While the groups discussed above were less popular during the Classic period, groups 3 and 4, referring to the solstices and quarter days of the year, were common throughout the history of the area (Figs. 4, 5, 6B, and 8A). Since the solstices are naturally significant moments of the tropical year, marked by easily perceptible extremes of the Sun's annual movement along the horizon, they must have been the most elementary references for keeping track of the seasons, as evidenced in many ancient cultures (*25*–*27*). Their importance in Mesoamerica, attested not only by architectural orientations but also by some glyphs and designs in prehispanic manuscripts, survives among various present-day indigenous communities, which often place the world corners at the solstitial points of the horizon (*2*, *28*, *29*). The next basic references in time computations must have been the quarter days: falling 1 or 2 days after/before the spring/fall equinox, they divide each half of the year delimited by the solstices in two equal parts. While there is no compelling evidence that the Mesoamericans were aware of the equinox as defined by modern astronomy (*30*), the importance of the solstices and quarter days is attested by architectural orientations throughout Mesoamerica (*4*).

The existence of solstitial alignments in the study area is better visible in Fig. 4A (concentration of declinations around ±24°) than in Fig. 4B, because the errors in azimuth around solstitial directions correspond to large errors in days, resulting in extended curves around the solstitial dates (for details, see text S2 and fig. S4). Quarter-day orientations are indicated by the clustering of declinations (around 0.7°), dates (around 22 March and 21 September), and intervals (around 182 days = 14 × 13 days) in Figs. 4 and 5. However, since quarter days were marked on both horizons, the KDE distributions of declinations and dates (Fig. 4) are affected by the merging of similar values. To avoid this effect, we plotted separately relative frequency distributions of dates corresponding on both horizons to negative declinations (from fall to spring equinox) and of those matching positive declinations (from spring to fall equinox). The distributions of both series of dates within a window of a few days around the equinoxes are shown in Fig. 9, together with the changing dates of quarter days from 900 BCE to 700 CE. The peaks corresponding to Formative and Classic period orientations closely agree with quarter-day dates in each period.

During the Classic period, some orientation groups apparently lost popularity, and some new groups appeared or became more prominent. Group 6 corresponds to sunrises on 1 March and 12 October, separated by 140 days. The intended referents of group 7 are less clear, but analogies from the Maya area suggest that some complexes in this group recorded sunsets on 29 March and 14 September, separated by 169 (= 13 × 13) days, and others sunrises on 11

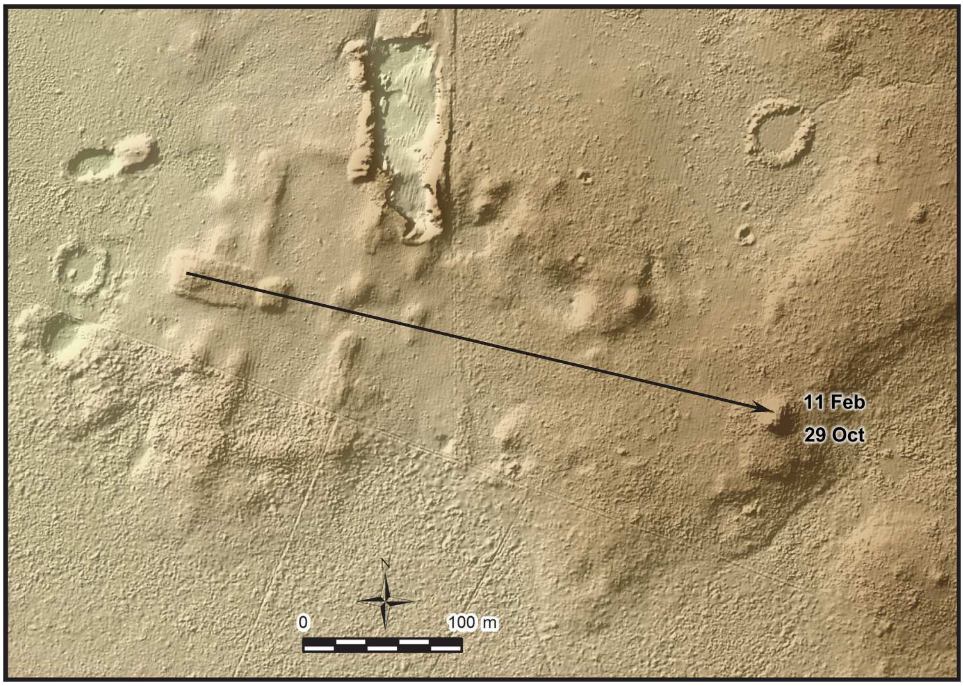

Fig. 7. Alignment of the central axis of MFU minor 22305 to a neighboring structure.

March and 2 October, with an intervening interval of 160 days (*5*, *24*).

We can detect additional possible orientation groups, which were also common in the Maya area and elsewhere in Mesoamerica. As suggested by alignments to mountain tops (which are hardly attributable to chance, given the analogies from a number of Mesoamerican sites) and other more accurately determinable orientations (text S4), it is particularly likely that group 1 represents a fusion of the prevalent one marking a 260-day interval (11 February and 29 October) with two or three others. One of them recorded sunsets on 30 April and 13 August, also separated by 260 days. An example of this orientation is the MFU complex of La Carmelita (Fig. 10) dated to 900 to 750 BCE (*15*). The second set marked 3 May and 11 August, and the third one 9 February and 1 November. Each of these date pairs is separated by 100 days.

While the solar orientations prevail in the study area, an astronomical basis is also very likely for a number of alignments beyond the solar angle. The orientations indicated by declination peaks near ±28° in Fig. 4A can be related to the major extremes of Venus and the Moon. The importance of both celestial bodies in Mesoamerica has long been known and is evidenced by a variety of prehispanic and early colonial written sources, iconography, and ethnographically documented survivals. A number of orientations to their extremes have also been identified (*2*, *4*–*6*, *31*–*35*). All Venus extremes are seasonal phenomena, but particularly interesting must have been those of the evening star, both because they are up to about 3° larger than those of the morning star (which never exceed notably the extremes of the Sun at the solstices) and because they approximately delimit the rainy season. Aside from the alignments marking the evening star extremes, there is other evidence that the Mesoamericans were aware of this seasonality, which thus very likely motivated the conceptual association of Venus, particularly its evening manifestation, with rain, maize, and fertility (*31*–*32*). Similarly, the Moon is almost universally associated with earth, water, and fertility (*36*). Various observational facts may have been responsible for these concepts, and there is evidence that some of them were perceived by the Mesoamericans. The existence of orientations to both Venus and lunar extremes in our study area is strongly suggested by the results of quantitative analyses of alignment data and additionally supported by different types of contextual evidence (for details, see text S2, figs. S4 to S6, and tables S2 to S4).

Last, the declinations clustering around ±37° (Fig. 4A) might be related to a star or a group of stars. As suggested by the analysis of the alignment data and analogies from elsewhere in the Maya Lowlands, the most likely referent was Fomalhaut (or an asterism in that part of the southern sky), whose heliacal rise (first visibility after sunrise) occurred in mid-February in the Formative but moved to March in the Classic (for details, see text S3, fig. S7, and table S5). The significance of this time span is evidenced by the dates recorded by solar orientations.

In several zones of the study area, many structures or architectural compounds are clustered and roughly reproduce the orientation of a major building. Similar cases, reflecting the importance of astronomically significant directions, have been documented at a number of Mesoamerican sites (*4*). At some sites, particularly those that exhibit clear grid patterns, the same celestial event could have been observed from different spots. At others, the dates marked by different orientations were separated by calendrically significant intervals, enabling the use of easily manageable observational schemes (for examples, see text S5 and figs. S9 to S12). Assuming that the observations were often hindered by unfavorable weather, the Sun watchers relying on various alignments had a

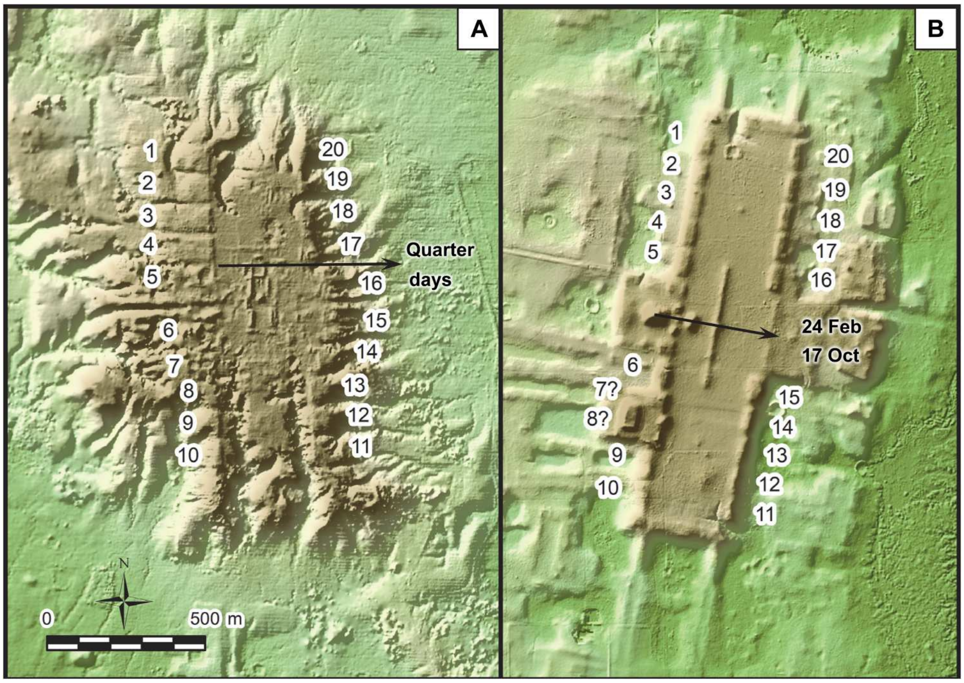

Fig. 8. Lidar-based images of two sites with similar spatial plans, each with 20 edge platforms. (**A**) San Lorenzo. (**B**) Aguada Fénix. Both images are on the same scale. Edge platforms 7 and 8 of Aguada Fénix were probably buried by the later addition of the Southwestern Platform. The orientation of San Lorenzo belongs to group 4 (quarter-day sunrises), whereas the orientation of the MFU and E-Group of Aguada Fénix belongs to group 2 (130-day interval).

better chance to predict the most important dates and to prepare the corresponding rituals with due anticipation.

DISCUSSION

Our finds accord well with the general patterns of astronomical observations, calendrical concepts, and early monumental constructions found across the world. Astronomical observations were practiced in many hunter-gatherer and horticultural societies, often focusing on the solstices, lunar cycles, and certain stars. Monumental constructions built before the full establishment of agriculture in various parts of the world commonly incorporated alignments to the solstices, lunar extremes, and possibly quarter days (*25*–*27*, *37*). With the establishment of agriculture, astronomical observations often became more important and elaborate (*38*, *39*). In various parts of Mesoamerica, maize appears to have been adopted as a staple crop at varying rates between 2000 and 1000 BCE (*40*, *41*). San Lorenzo, with its heyday between 1400 and 1100 BCE, was probably built by people relying heavily on the wild resources of the surrounding rivers and wetlands (*42*). Its main plateau is oriented to quarter-day sunrises, but its 20 edge platforms suggest that calendrical concepts based on the number 20 were already in place. Moreover, observing from the core area of San Lorenzo, the Sun at the December solstice sets behind Mt. Zempoaltépetl in Oaxaca, which is still a sacred and ritually important mountain for the local Mixe. The importance of solstitial directions continued during the following Middle Formative period, particularly in the regions south of our study area, including central Chiapas and the Pacific Coast (*6*, *43*).

During the Early-Middle Formative transition around 1100 to 900 BCE, monumental ceremonial constructions spread to a wide area with the establishment of MFUs and other standardized complexes. Various Mesoamerican communities of this period were adopting more sedentary lifestyles along with a stronger commitment to maize agriculture, while some groups still maintained the Archaic ways of life. In this regard, these constructions reflect social contexts comparable to those of early monuments that were built in other parts of the world during the transitional stages toward agriculture or incipient agricultural periods, such as Göbekli Tepe in Turkey and Caral in Peru (*44*–*46*). These constructions possibly symbolized a sense of attachment to fixed localities and provided concrete images of communal collaboration that could be shared among the growing populations (*13*, *15*, *27*, *47*–*49*). Along with the orientations tied to the solstices and quarter days, MFUs and other standardized complexes of our study area began to exhibit more diversified alignments. The new orientations reflect the use of observational schemes based on the 260-day calendar and its constituent periods of 13 and 20 days. Since solar horizon calendars can only function through observations made from a fixed spot (*26*), a factor underlying this development must have been the increasing adoption of more sedentary ways of life. While mobile and sedentary groups may have coexisted in various parts of Mesoamerica (*13*, *50*–*52*), more sedentary groups probably resided at large centers, including San Lorenzo and Aguada Fénix. These groups possibly included ritual specialists, who held esoteric knowledge of astronomical observations and played a leading role in the sophistication of calendrical concepts.

While we recognize these common trends in the development of astronomical observations and monumental constructions shared with other parts of the world, the 260-day calendar is a cultural feature unique to Mesoamerica. To explain the development of this calendrical system and its incorporation into early ceremonial

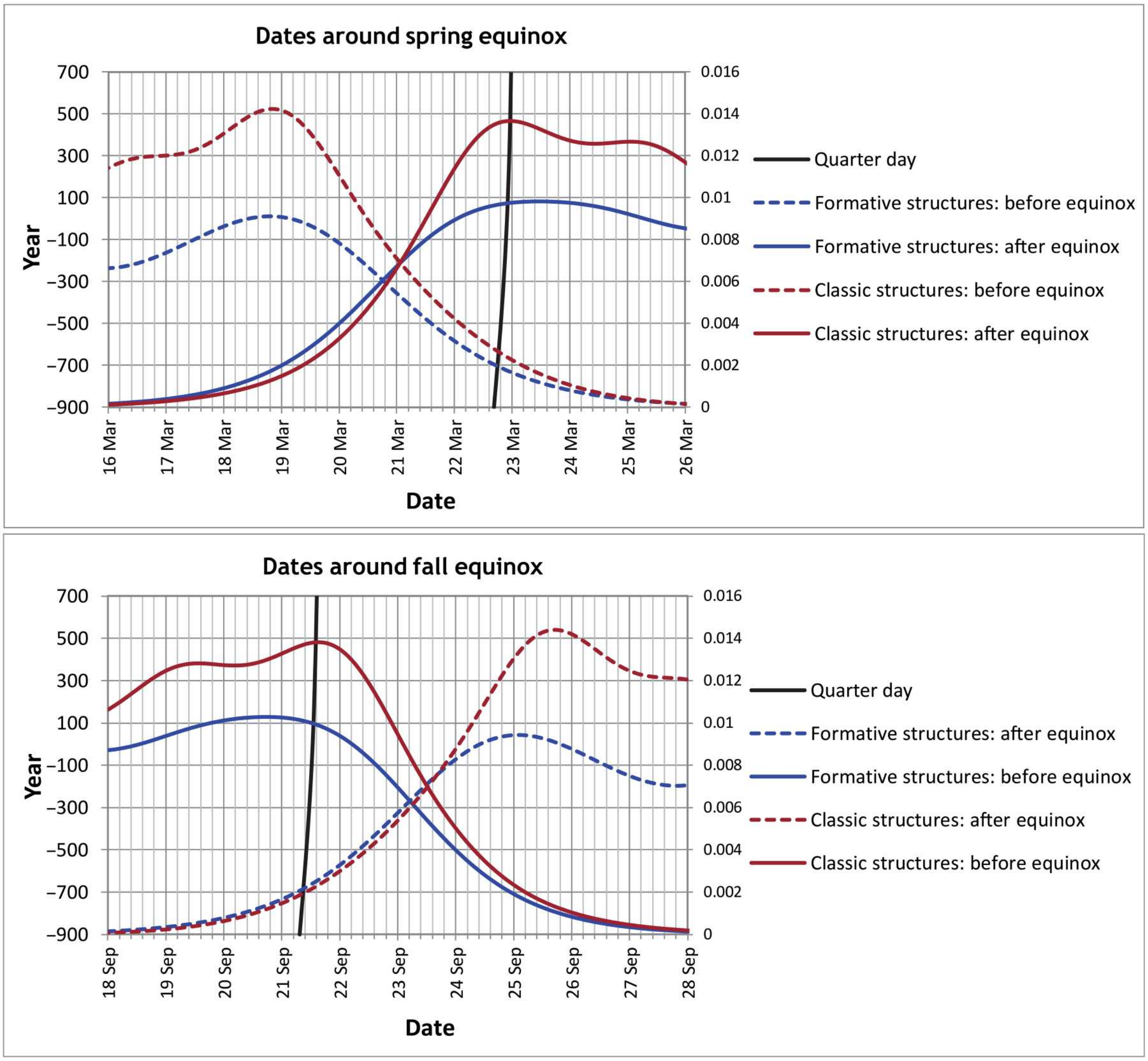

Fig. 9. Relative frequency distribution of dates falling within a few days before and after the spring and fall equinoxes, compared with varying quarter-day dates during the relevant period. The exact moments of quarter days were determined for a few years (900, 450, and 50 BCE and 350 and 700 CE) by halving the time spans delimited by the exact moments of solstices in those years (based on solar ephemeris data calculated by Horizons web-interface provided by the Solar System Dynamics Group, NASA Jet Propulsion Laboratory; https://ssd.jpl.nasa.gov/?horizons).

buildings, we need to explore the specific cultural and ecological conditions of Mesoamerica, along with the commonalities with other regions. The origins of the 260-day calendar have long been debated. Scholars have proposed possible underlying reasons, including numerology, agricultural scheduling, the human gestation period, and the interval between solar zenith passages (*53*–*55*). By numerology, we refer to a culturally shaped concept that gives religious and cosmological meanings to certain numbers, which may be associated with the occurrences of certain events in the social and natural world. For the Maya and other Mesoamerican groups, numbers 20 and 13, associated with human body parts, particular deities, and cosmic levels, were particularly important. Although our data are not enough to resolve the origin of the 260-day calendar, they lead us to favor two alternative scenarios, each combining the numerology and the scheduling of rituals.

In the first scenario, this process possibly emerged within the preexisting tradition of annual aggregation and dispersal of mobile groups, which is also observed among ethnographically known hunter-gatherers and horticulturalists. Some preagricultural monumental constructions found outside Mesoamerica, including Göbekli Tepe or Poverty Point, were most likely built during periods of seasonal gathering (*27*, *46*). In the tropical lowland areas of Mesoamerica, the height of the dry season around February and March, when horticulturalists were freed from their work in cultivation fields, was most likely the time of aggregation during the Archaic and Early Formative periods. In addition, as river and lake water receded to smaller areas during the dry season, fish and shellfish became more easily accessible in concentrated forms. In particular, fish trapped in oxbow lakes that are detached from rivers during this period were easy targets for fishing. Many Formative complexes thus are found near the bodies of water. In April, many people probably began to return to dispersed settlements to prepare their cultivation fields before the first rain came in May. They may also have

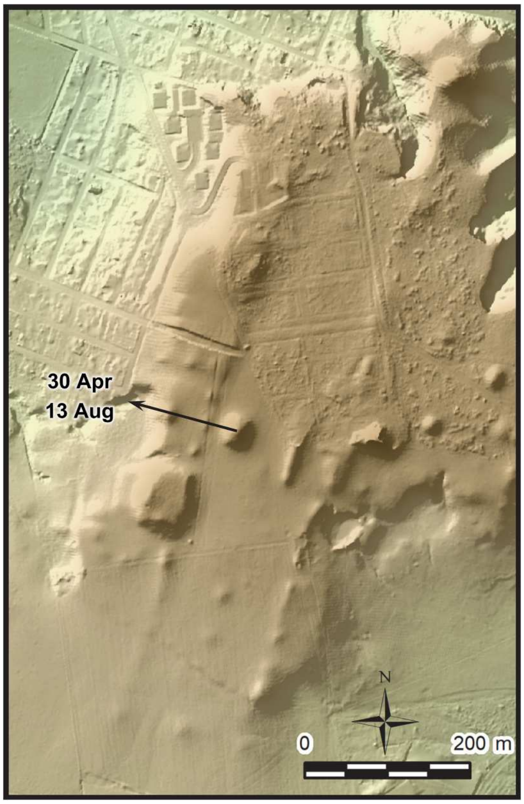

Fig. 10. MFU 14267 (La Carmelita). The central E-W axis of the E-Group matches sunsets on 30 April and 13 August, which could have been observed from the highest pyramid over a smaller one to the west.

relied more on dispersed wild resources in the forest during the rainy season.

The concentration of solar alignments corresponding to dates in February and March in our study area possibly reflects this period of aggregation, collective ritual, and construction activity. To coordinate ritual schedules among participants from ever broader areas, the builders of ceremonial complexes needed to elaborate solar observational calendars, which were incorporated in building designs (*27*). Although major centers, such as San Lorenzo, may have been primary locations for the initial development of solar calendars, once they were established, they could have been practiced in many places. Knowing that major rituals took place on specific dates of a solar calendar, those who resided in distant places could use solar observations to know when to go to communal ceremonial complexes without the benefit of communication systems over long distances. These ritual calendars were tied to the Mesoamerican numerology of 20 and 13, resulting in the 260-day calendar. In addition, the earlier use of stars and the Moon for timekeeping may be reflected in the alignments of some complexes with lunar extremes and with a star or asterism whose heliacal rises fell in February and March (text S3).

The second possibility is that the dates most frequently recorded by solar alignments marked rituals of predominantly agricultural significance, as suggested also outside Mesoamerica (*27*, *56*). The emergence of standardized complexes tied to the 260-day calendar in our study area around 1000 BCE may be related to the spread of maize agriculture. This scenario is supported by the persistence of prominent orientation groups in later periods and by modern ethnographic data. Many dates marked by architectural orientations are in remarkable agreement with the timing of agricultural rituals performed by modern communities, although many of them are blended with Christian ceremonies. Some communities still use the 260-day calendar to schedule agricultural rituals that inaugurate particular stages of the canonical 260-day maize cultivation season (*4*–*6*). Despite possible variations in agricultural scheduling due to different ecological settings and farmers' individual decisions, this persistence in architectural orientations and ritual dates across time and space implies that agricultural activities were shaped by shared calendrical concepts.

Although various scholars have suspected that the 260-day calendar was established during the early Middle Formative period or earlier, it has been difficult to test this idea because of the absence of sophisticated writing systems in those periods. Our alignment data provide evidence that this calendar was in use during the period between 1100 and 750 BCE. The specific designs of MFU and other complexes from their initial construction and the presence of 20 edge platforms at San Lorenzo suggest the possibility that the 260-day calendar or related concepts existed even before 1100 BCE. Our data are consistent with the hypothesis that the Gulf Coast Olmec region and adjacent areas were the primary stages for the initial development of the Mesoamerican calendrical system and astronomically oriented monumental architecture.

Last, the results of our study exemplify the relevance of archaeoastronomical approach to understanding the role of astronomy in site organization and landscape formation. Recent research in different parts of Mesoamerica has led to substantial progress in unveiling the astronomical principles underlying architectural design and urban planning, but these findings have been largely overlooked in mainstream archaeological literature. While settlement patterns, architectural configurations, and urban layouts have been the subject of numerous studies, the orientations and their implications are rarely even mentioned. In our study area, like elsewhere, the alignments based on astronomical and calendrical criteria were not only embedded in important civic and ceremonial buildings but were often also reproduced, albeit not always with observationally functional accuracy, by many surrounding constructions, frequently dominating considerable parts of the built environment. Consequently, the importance of the astronomically significant directions and related concepts allows us to understand some prominent aspects of architectural ground plans, urban patterns, and even broader cultural landscapes.

MATERIALS AND METHODS

Alignment measurements

The orientations were measured on digital elevation model (DEM) derived from airborne laser scanning (lidar) data, using ArcGIS software and different types of visualizations. Depending on the resolution of lidar data from different sources (*13*, *15*), possible errors were estimated and assigned to each alignment. Both N-S and E-W alignments were determined for each structure or compound (or only one, if the other was not determinable). Each alignment corresponds to the E-W or N-S axis of a building or to a series of evidently aligned structures. Where several nearly parallel lines were determinable, the mean value of their azimuths was calculated. Observation points, required for calculating horizon altitudes, were placed on an elevated and presumably the most convenient spot of each architectural structure or complex. Although the locations of these points are hypothetical, the differences regarding the true observation points have no major relevance, because the horizon line is in most cases far away. The azimuths of alignments measured in Universal Transverse Mercator (UTM) cartographic projection were corrected to true (astronomical) azimuths for grid convergence, calculated with ArcGIS tools.

All the alignments measured are listed in table S1. Since the astronomical basis of N-S alignments is unlikely (see the "Analyses" section), the analyses were focused on the data corresponding to E-W alignments (45° ≤ azimuth ≤ 135°). These were determined for 66 MFU, 31 VC, 5 MFC, and 3 MFG complexes, 52 Rectangles, 8 Squares, 19 E-Groups, 114 Classic Veracruz complexes, and 46 Classic structures of other types (Classic generic). If the type is labeled "MFU & E-Group" in table S1 (or "VC & E-Group", or alike), then it means that both the large complex and the integrated E-Group have the same orientation, which was considered as a single one in the analyses. However, where the E-Group has a different orientation (i.e., the differences in azimuth are not within the range of error estimated for each alignment), the alignment data for both the larger complex (MFU, VC, etc.) and the integrated E-Group (labeled "MFU E-Group," "VC E-Group," etc.) are given and were included in the analyses.

Data reduction

Putative astronomical target(s) of an alignment can be identified only by calculating the corresponding declination (celestial coordinate that expresses angular distance measured from the celestial equator to the north and south and depends on the azimuth of the alignment, geographic latitude of the observer, and the horizon altitude corrected for atmospheric refraction). The declinations were calculated with the formulae of spherical astronomy routinely used in archaeoastronomical research (*2*, *6*, *25*). Horizon altitudes required for these calculations were obtained with the Horizon software (http://agksmith.net/horizon/default.html), using 1–arc sec (30 m) Shuttle Radar Topography Mission (SRTM) data (www2.jpl.nasa.gov/srtm/). The orthometric height of each observation point was determined on the lidar-derived DEM. The latter, although more accurate than SRTM, was not convenient for calculating horizon altitudes both because the horizon line in many cases lies beyond the area covered by lidar and because the Skyline tool in ArcGIS is less precise and practical than the Horizon software. However, in the cases where the horizon line is relatively near, horizon altitudes were calculated from the lidar-based DEM. In these calculations, the height of forest canopy was considered to have been 15 m, except in the area of clearance surrounding the observation point within the radius of 3000 m. The errors resulting from this inevitably arbitrary decision are small and probably negligible, because the horizon line is, in most cases, several kilometers away. While horizon altitudes were always corrected for atmospheric refraction (*57*), the altitudes of distant points (over 80 km away) were determined with the online calculator provided by A. T. Young, in which terrestrial refraction is also taken into account (https://aty.sdsu.edu/explain/atmos_refr/altitudes.html). For the alignments potentially related to lunar extremes, geocentric lunar declinations were calculated, considering the parallax (*25*, *58*).

The declinations within the solar span were converted to Gregorian dates and the intervening intervals were also calculated. Since the Sun attains a certain declination (except a solstitial one) twice a year, two sunrise and two sunset dates correspond to each alignment and each date pair divides the year into two intervals, whose sum is equal to the length of the tropical year (currently about 365.2422 days). The dates are given in the proleptic Gregorian calendar (extrapolated into the past before its actual introduction), which is the closest approximation to the tropical year, and are valid for the period of construction of the building in question. Because of secular variations affecting the obliquity of the ecliptic, the length of the tropical year and the heliocentric longitude of the perihelion of Earth's orbit (the latter element determining the length of astronomical seasons), on the one hand, and to the Gregorian calendar intercalation system, on the other, one and the same solar declination does not always correspond to exactly the same Gregorian date. For the three main periods in which the sites in our area flourished (early and middle phases of Middle Formative and Late Classic), three ordinary Julian years were chosen for computations (900 BCE for MFU, VC, E-Groups, Rectangles, and Squares; 600 BCE for MFC and MFG; and 700 CE for Classic Veracruz and Classic generic sites; for the Late Formative El Tiradero, year 50 BCE was used). For each of these years, solar ephemeris data were generated, using Horizons web interface provided by the Solar System Dynamics Group of the NASA Jet Propulsion Laboratory (https://ssd.jpl.nasa.gov/horizons/). A list containing the Sun's apparent geocentric declinations calculated for the whole year at intervals of 6 min, as well as the corresponding Julian dates and hours, was downloaded and imported to an Excel table. To obtain comparable dates, the moment nearest to the March equinox (when the Sun's declination was nearest to 0°) was, in all cases, taken to be March 21.0, Gregorian (21 March, at 0:00 hours of Universal Time) and all other Julian dates and hours in the table were corrected accordingly. Then, the differences between all the declinations listed in the table and the declination corresponding to a particular alignment were calculated; after finding the smallest two differences, which indicated the two Gregorian dates matching the alignment's declination, the intervening intervals were calculated. One of the two intervals was the exact difference between the two dates, but since one table of ephemeris data comprised only 1 year, the complementary interval was calculated by subtracting the other from the length of the tropical year, calculated for the year in question with the algorithm given by Meeus and Savoie (*59*). As the same procedure had to be repeated for all declinations targeted by the alignments included in the study, a macro routine in Excel was created for these computations. In this routine, the errors of dates and intervals, based on the errors of declinations (which are the same as those estimated for the corresponding azimuths), were also calculated. All these data are listed in table S1.

It may be necessary to clarify that, if the true moment of the equinox in each year used for determining the dates had been considered, the analysis of their distribution would yield unreliable results, since the exact date corresponding to one and the same declination in different years presents variations of up to about ±1 day, depending on the placement of the year in a 4-year cycle and within a 4-century period of the Gregorian intercalation system. By correlating the vernal equinox invariably with March 21.0, one and the same declination corresponds to the same dates during at least two or three centuries; inaccurate chronological placements of particular structures thus have no major relevance. Because of the aforementioned secular variations in Earth's orbital elements, the declination corresponding to one and the same date slightly changes over longer time spans, resulting in that the exact dates delimiting a certain interval may also present minor shifts. However, the differences in comparison with the "ideal" dates given in the text and corresponding to particular orientation groups rarely amount to more than a day (e.g., the 260-day interval was delimited by 11 February and 29 October during the Formative, while in the Late Classic and afterward, the dates tended to be 12 February and 30 October).

As the azimuths of many alignments cannot be accurately determined (due to the current state of the structures and the resolution of lidar-derived DEM) and considering the uncertainties regarding the exact location of observation points (on which horizon altitudes depend), the attempt to achieve the precision in determining dates and intervals might appear an exaggeration. However, this effort seemed preferable, so as not to increase the errors that are inevitable.

Analyses

In the analyses of alignment data, KDE was used (Figs. 3 to 5). An advantage of this method over simple histograms (figs. S1 to S3) is in that the errors assigned to individual values are taken into account. In KDE analyses, each datapoint is replaced by a weighting function (kernel) with a specified distribution and a smoothing parameter (bandwidth). While there are different kernel types (*60*), we used the Gaussian kernel, with a normal distribution centered on the nominal value and with a standard deviation (bandwidth) equal to the error assigned to each value. All normal distributions (kernels) were then summed up and plotted, using MS Excel Add-in Kernel.xla 1.0e (developed by Royal Society of Chemistry and downloadable as Kernel.zip at https://rsc.org/membership-and-community/connect-with-others/join-scientific-networks/subject-communities/analytical-science-community/amc/software/, tab "Software for calculating kernel densities"). Since the errors assigned to similar values tend to cancel out, it can be expected that the most prominent peaks of the resulting curves, which present relative frequency distributions (Figs. 3 to 5), closely correspond to the values targeted by particular orientation groups (graphs of this type have also been named "curvigrams" or "cumulative probability histograms") (*25*).

The nonuniform distribution of azimuths (Fig. 3 and fig. S1) suggests an astronomical rationale. In addition, the distributions of the corresponding declinations and dates (Fig. 4 and figs. S2 and S3) are different from those resulting from a uniform or homogenous distribution of azimuths [see figures 2 and 4 in (*60*)]. However, it is unlikely that the N-S alignments were conditioned by astronomical criteria because of the following:

1) The azimuths of both Preclassic and Classic buildings tend to cluster around similar values, but the clustering is more pronounced in the distribution of E-W azimuths.

2) There are few bright stars in the northern and southern sky and their rising or setting points cannot account for the peaks in Fig. 3 (the concentrations of N-W azimuths can be attributed to the fact that in many constructions they are more or less perpendicular to the E-W azimuths).

The distribution of declinations marked by N-S azimuths has not been analyzed, because their clustering is even less pronounced than that of the azimuths (the difference between declinations corresponding to different N-S azimuths is much smaller than the variation in declination corresponding to the same azimuthal difference on the eastern or western horizon). In addition, without any independent evidence suggesting a stellar target, we cannot calculate declinations by applying the correct extinction angle (the minimum angular altitude above the horizontal plane at which a star is visible and which depends on its magnitude; note that the declinations corresponding to N-S alignments, given in table S1, were calculated without considering any extinction angle). Therefore, even if the possibility that some of the N-S alignments had stellar referents cannot be discarded outright, no plausible hypothesis can be based on the alignment data alone.

Given these arguments, our analyses were focused on the data corresponding to the E-W alignments. As mentioned above, the prominent peaks in KDE graphs are indicative of intended values. However, a few notes are in order.

Because of the estimated errors of azimuths (the same errors were assigned to declinations), the values corresponding to nearby orientation groups tend to merge and some of the intended values are obscured in KDE graphs. In addition, since the celestial referents corresponding to each alignment in both directions were considered in the analyses, although most alignments were likely functional only in one direction (as previous work elsewhere in Mesoamerica has also shown), several peaks of the KDE curves represent unintended values. Further, while the orientations in Mesoamerican architecture are characterized by a prevalent south-of-east skew [for possible reasons, see (*61*)], 110 structures in our data sample (32%) are deviated north of east. As certain celestial events were marked on either the eastern or the western horizon, the targeted and unintended values often blend in the graphs. Last, a considerable number of structures probably were not oriented astronomically, contributing to the "noise" in data distribution.

Supplementary Materials

This PDF file includes:

Texts S1 to S5
Figs. S1 to S12
Tables S2 to S7
References

Other Supplementary Material for this manuscript includes the following:

Table S1

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