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Origins and spread of formal ceremonial complexes in the Olmec and Maya regions revealed by airborne lidar

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City plans symbolizing cosmologies have long been recognized as a defining element of Mesoamerican civilizations. The origins of formal spatial configurations are thus the key to understanding early civilizations in the region. Assessment of this issue, however, has been hindered by the lack of systematic studies of site plans over broad areas. Here, we report the identification of 478 formal rectangular and square complexes, probably dating from 1,050 to 400 BC, through a lidar (laser imaging, detection and ranging) survey across the Olmec region and the western Maya lowlands. Our analysis of lidar data also revealed that the earlier Olmec centre of San Lorenzo had a central rectangular space, which possibly provided the spatial template for later sites. This format was probably formalized and spread after the decline of San Lorenzo through intensive interaction across various regions. These observations highlight the legacy of San Lorenzo and the critical role of inter-regional interaction.

The layouts and orientations of Mesoamerican cities were closely tied to cosmologies, concepts of time and ritual practices[1,2]. Formal site plans dating to the Early Formative (1,800–1,000 BC) and Middle Formative (1,000–350 BC) periods may have provided symbolic templates for later urban formations, and thus the origins and development of early standardized spatial configurations present critical information for the understanding of social and cultural processes in Mesoamerica. An important area in this regard is the Isthmian region of southern Mexico and western Guatemala, encompassing the Gulf Olmec region, where Olmec centres, such as San Lorenzo and La Venta, developed during the Early and Middle Formative periods, and the western Maya lowlands, where many Maya centres emerged during the Late and Terminal Formative periods (350 BC to AD 250) and the Classic period (AD 250–950). These regional names simply follow scholarly conventions, and our use of those names does not imply the ethnic or linguistic identities of the inhabitants during the Early and Middle Formative periods.

The spatial configuration of La Venta is known as the Middle Formative Chiapas (MFC) pattern, which comprised a central precinct called an E Group (consisting of a western square or conical building and an eastern elongated platform), large platforms arranged along the north–south axis and a northern pyramid[3–6]. The MFC format is also found in contemporaneous centres in central and southern Chiapas, including San Isidro, Chiapa de Corzo and Tzutzuculi (Fig. 1). Excavations revealed caches containing greenstone axes on the axes of the E Groups and other locations at some MFC centres[7–9]. These data suggested to some scholars that these spatial formats were invented at La Venta (its heyday between 800 and 400 BC) and then were passed on to other groups, along with associated cultural elements[3,4]. Other scholars opposed the theory of one-directional influence from La Venta and argued for the parallel development of early Mesoamerican societies[10]. However, the identification of the MFC pattern with greenstone axe caches at Ceibal in the southwestern Maya lowlands dating to 950 BC (thus predating the growth of La Venta), as well as re-evaluations of data, suggested that the patterns of inter-regional interaction were complex[11–13].

The role of the earlier Gulf Olmec centre of San Lorenzo (its apogee between 1,400 and 1,150 BC) in the development of standardized spatial forms was not clear. Although some scholars have argued that characteristic styles of stone sculptures and ceramics were developed at San Lorenzo and then spread to other parts of Mesoamerica[14,15], the influence of this centre on the spatial forms of other sites has rarely been discussed. The site of San Lorenzo consisted of a large plateau and no pyramidal buildings appear to have existed during its Formative apogee. Michael Coe proposed that the San Lorenzo plateau was an effigy monument representing the shape of a giant bird[16]. Cyphers and others, however, have argued that the gullies and ridges are results of erosion[17,18]. All in all, the site plan of San Lorenzo has been seen as unique and disconnected from later standardized formats, and the presence of standardized complexes in the area to the west of La Venta has not been reported.

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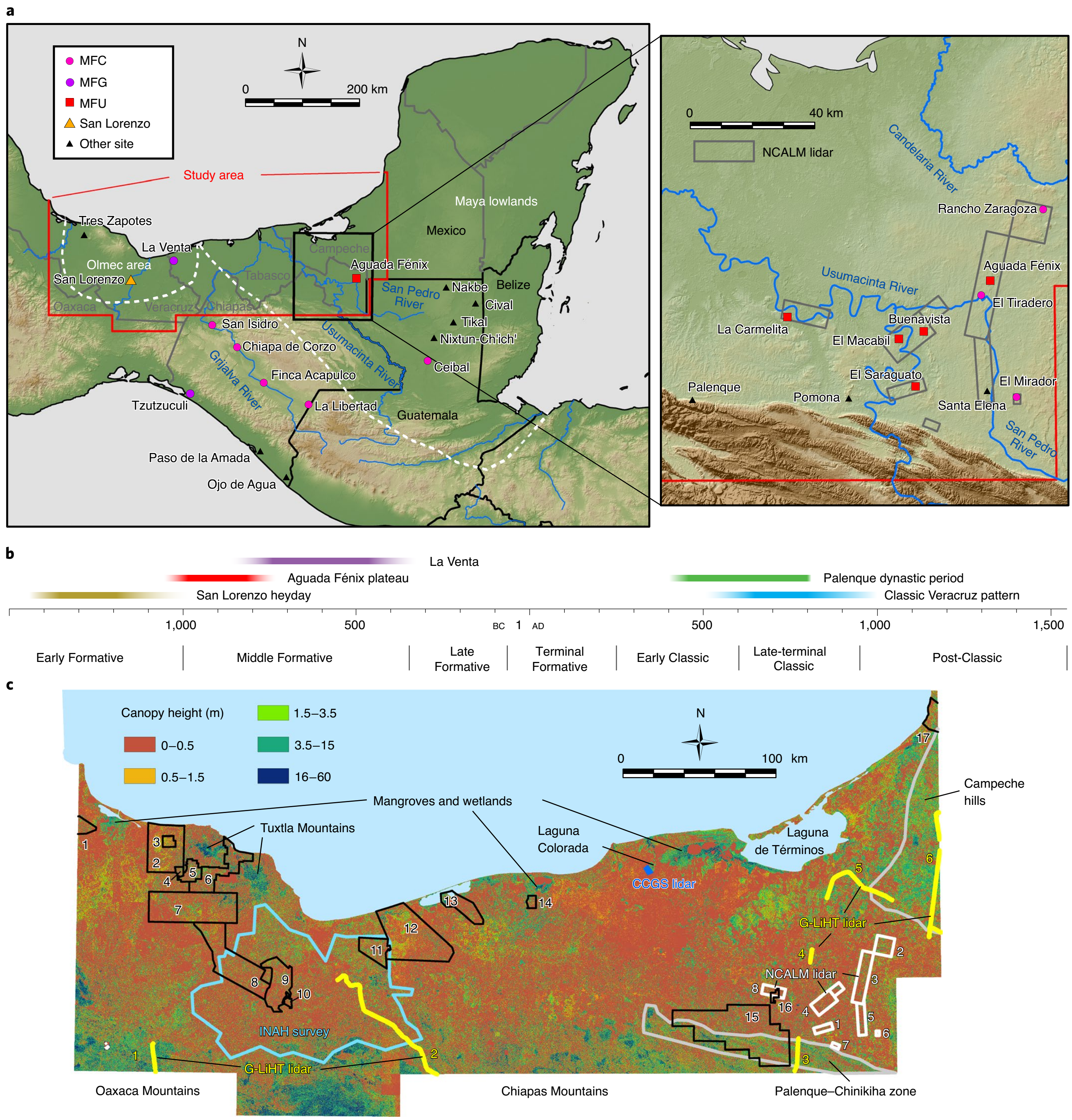


Fig. 1 | Study area. a, Map of southern Mesoamerica with the study area. The close-up map shows the Middle Usumacinta region where we conducted field investigations. **b**, Chronology of the study area. **c**, Canopy height model (CHM) at a horizontal resolution of 5 m based on the INEGI lidar, indicating the heights of vegetation. The Campeche hill area and the Palenque–Chinikiha zone are particularly problematic areas, where numerous archaeological features exist, but dense vegetation inhibits their detection with the INEGI lidar. The blue polygon indicate the coverage of the Centro INAH Veracruz survey[124–133] and the black ones show the areas of other systematic ground surveys carried out before this study. In most cases, intensive surveys were conducted for sample blocks within each of those polygons, and thus the ground survey coverage is substantially smaller than the polygons. 1, Mixtequilla Survey[71,134,135]; 2, Tres Zapotes Survey[69]; 3, El Mesón Survey[136]; 4, Cerro El Vigía Survey[137]; 5, Tepango Valley Survey[117]; 6, Tuxtla Region Survey[118,138]; 7, Hueyapan Survey[68,70]; 8, San Lorenzo-Laguna de los Cerros Survey[61]; 9, San Lorenzo Survey[62]; 10, Region of the Olmec Survey[121]; 11, Río Pesquero Survey[139]; 12, La Venta Survey[122]; 13, Pajonal Survey[63]; 14, Comalcalco Survey[140]; 15, Palenque Survey[64];16, Cuenca Medio del Usumacinta Survey[141]; and 17, Río Champoton Survey[142].

In this regard, the lack of systematic investigations of site plans over broad areas has hindered our understanding of early formal spatial configurations.

We started the Middle Usumacinta Archaeological Project (MUAP) in 2017 in eastern Tabasco and recently reported that the artificial plateau of Aguada Fénix, a rectangular construction

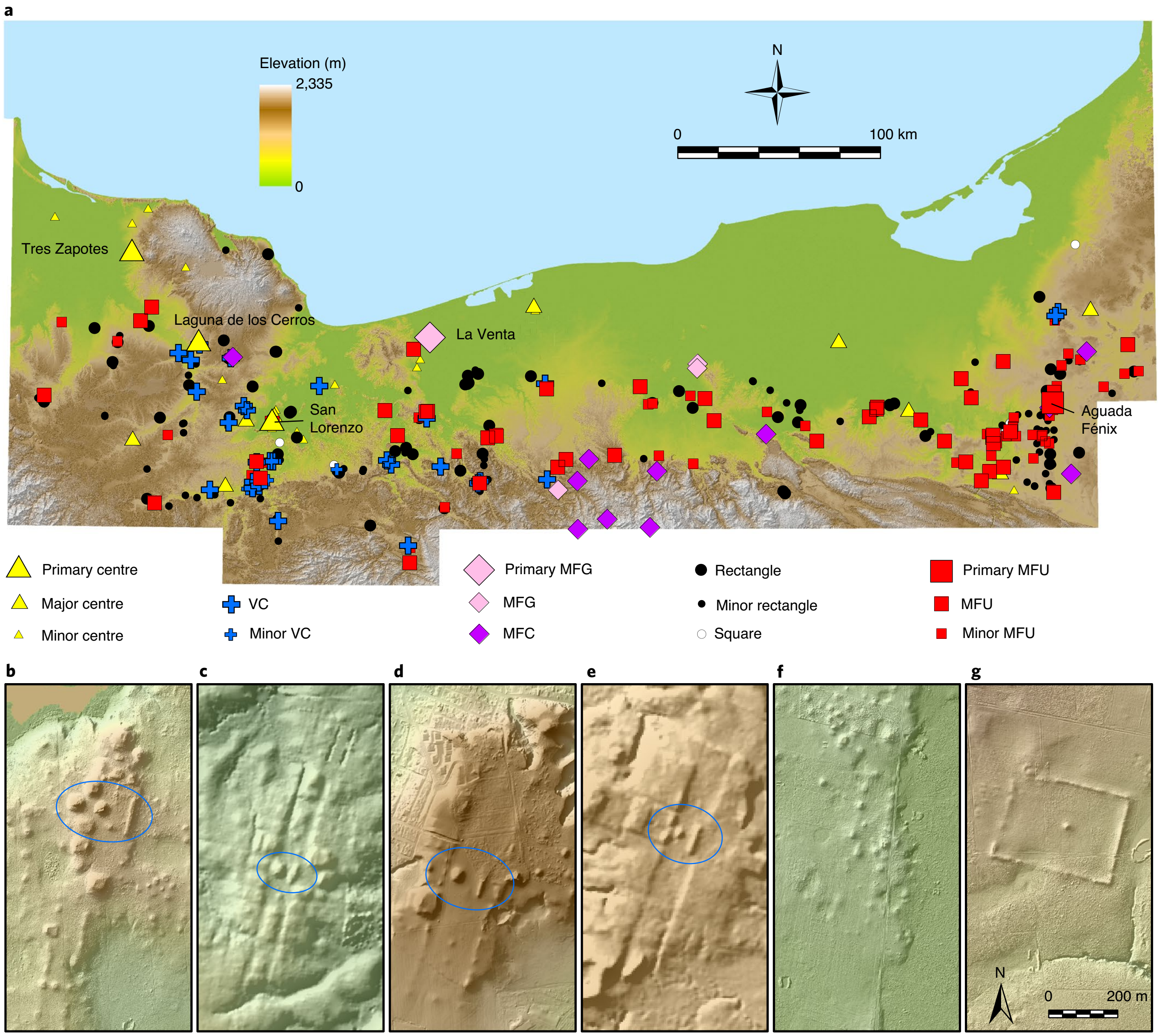


Fig. 2 | Formative standardized complexes. a, The locations of standardized complexes in the study area. Only complexes identified in the INEGI lidar are plotted. **b**–**g**, Examples of standardized complexes: MFC (Rancho Zaragoza) (**b**); MFG (Pajonal) (**c**); MFU (La Carmelita) (**d**); VC (Uxpanapa) (**e**); rectangular complex (Fideicomiso) (**f**); and square complex (La Veleta) (**g**). E Groups are circled in blue. All images are on the same scale.

measuring 1,413 m in length, 399 m in width and 10–15 m in height, represented the earliest and largest monumental building in the Maya area[19]. As we recognized similar rectangular complexes in the region, we called this formation the Middle Formative Usumacinta (MFU) pattern. The presence of this previously unrecognized pattern implies that the emergence of standardized ceremonial complexes in southern Mesoamerica was more complex than previously thought. To examine the development of ceremonial complexes and associated social processes in a broader area, we expanded our research to an area of 84,516 km^2, including the Olmec region and the western Maya lowlands (Fig. 1).

Our research primarily used lidar (laser imaging, detection and ranging) data obtained by the Instituto Nacional de Estadística y Geografía (INEGI). In areas with dense vegetation, the use of airborne lidar is becoming common, but a major limitation is its high cost. In Mesoamerica, most lidar surveys have been limited to regional scales in areas of around 2,000 km^2 or less[20–24]. This situation is gradually changing with an increase in broad-area lidar data[25–28]. The INEGI lidar has low data densities around 0.03 pulses m^{-2}. To examine its effectiveness in archaeological research, we compared it with high-resolution lidar data (around 6–15 pulses m^{-2}) of selected areas, including those obtained by the National Center for Airborne Laser Mapping (NCALM) and the NASA Goddard's LiDAR, Hyperspectral & Thermal Imager (G-LiTH). A large part of the study area has been deforested and under these conditions the INEGI lidar, combined with the NCALM and G-LiTH data, led to the identification of numerous complexes (Supplementary Discussion 1, Supplementary Figs. 1 and 2 and Supplementary Tables 1–3).

To verify the results of the lidar analysis, the MUAP conducted pedestrian surveys of 62 sites in the Middle Usumacinta region and excavated Aguada Fénix, El Tiradero, La Carmelita, Buenavista and Rancho Zaragoza. In addition, we compared the lidar data with the results of earlier ground surveys, including the one carried out in

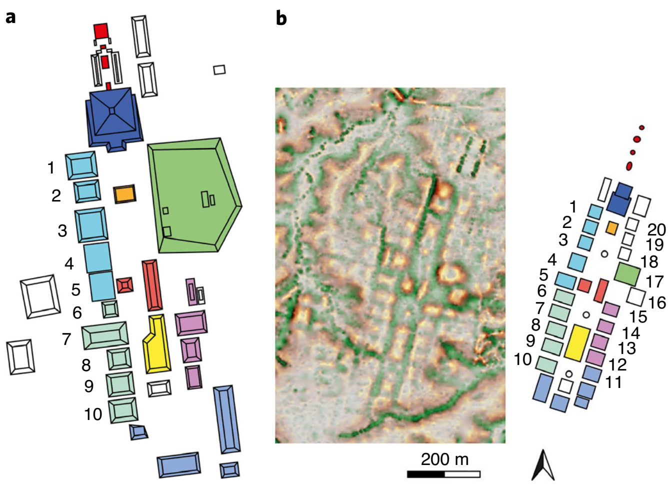


Fig. 3 | MFG complexes on the same scale. a, La Venta. Redrawn from ref. [143] with authorization by the Instituto Nacional de Antropología e Historia, SECRETARIA DE CULTURA.-INAH-MEX. **b**, Pajonal. It closely replicates the spatial configuration of La Venta, although in a smaller size. This site may replicate the 20 edge platforms seen at San Lorenzo and Aguada Fénix. The corresponding structures of the two sites are indicated by the same colours. Structures in red form E Groups.

southern Veracruz by the Veracruz office of the Instituto Nacional de Antropología e Historia (Centro INAH Veracruz). These surveys and excavations provided important data for the initial evaluation of the lidar analysis. More extensive ground investigations in such a broad area require many years of work. Development in remote sensing has demonstrated that spatial analysis on inter-regional scales, even without thorough ground investigations, can make transformative effects on archaeological practices and understandings[29,30]. An effective strategy in inter-regional studies may not necessarily be to conduct field investigations over the entire area immediately following remote-sensing analysis but to develop probable interpretations and hypotheses by combining the remotely sensed data with available survey and excavation data. Such hypotheses should encourage and guide future field investigations by many researchers.

We should also consider the potential shortcoming of ground observations. Ground verifications are important for small archaeological features, but for extensive archaeological features, such as large platforms and complexes, ground observations may not always provide better results than lidar. Horizontally large features are difficult to perceive accurately for an observer standing on a ground level, and their shapes may not be correctly mapped even when measured with a theodolite or total station. In general, maps based on ground surveys tend to depict large rectangular platforms in amorphous or roundish shapes. For example, the artificial plateau of Ceibal was presented in an amorphous shape in the otherwise excellent map of the site. Its well-designed shape with sharp edges became clear only through lidar[31,32]. Even in a deforested area, the extensive basal platform of Izapa Mound 30 was depicted with roundish edges in the archaeological map, and lidar revealed its rectangular shape[33,34].

Results

Standardized complexes. In addition to the previously reported MFC and MFU patterns, we defined additional types of early formal site plans: the Middle Formative Gulf (MFG) pattern and the Veracruz Ceremonial pattern (VC) (Fig. 2 and Supplementary Table 4). Their names reflect the areas where they were first identified, not their places of origin. Throughout the study area, many of these complexes contain an E Group in the centre. We also identified simpler forms of complexes without an E Group, which we call rectangular and square complexes (Fig. 2). These complexes, including MFCs and MFUs, total 478 and are distributed across the entire study area, encompassing the western Maya lowlands and the Olmec region (Supplementary Discussion 2 and Extended Data Fig. 1). Although a small number of them was previously reported[35–37], in most cases their formal configurations were not fully recognized.

We created the category of MFG as a subtype of the MFC pattern (Fig. 3 and Extended Data Fig. 2). We classified La Venta and similar sites into the MFG pattern, which exhibits neatly aligned platforms along straight lines. We suspect that most MFC and MFG sites in the study area are contemporaneous with La Venta and central Chiapan centres, which reached their apogees between 800 and 400 BC (refs. [4,7,11,38]). Communities in eastern Tabasco may have adopted the MFC pattern from those in western Tabasco and central Chiapas. Our excavation data indicate that the MFC complex of Rancho Zaragoza was occupied in the Middle Formative period and continued into the Late and Terminal Formative periods, whereas El Tiradero was constructed mainly during the Late and Terminal Formative periods.

The MFU pattern exhibits certain similarities to the MFC and MFG patterns, including an E Group and a general north–south orientation, but it is distinguished by a rectangular formation defined by lines of low mounds (Extended Data Figs. 3 and 4). Unlike the artificial plateau of Aguada Fénix, most MFU complexes do not have a raised plateau, and their rectangular formations are delineated roughly at the same level as the surrounding ground. Our excavations suggest that MFU complexes in the Middle Usumacinta region date between 1,050 and 750 BC or possibly earlier (Supplementary Discussion 4, Supplementary Method, Extended Data Fig. 5 and Supplementary Table 8). The VC pattern is a possible variant of the MFU pattern. This format has a rectangular form similar to the MFU pattern, but a projection defined by linear mounds is attached to the rectangle, usually on the west side (Extended Data Fig. 6). At many VCs, the edges of the rectangular forms and the projections were defined by continuous, long platforms rather than discrete mounds. Some VC complexes have an E Group, whereas others do not. We classify Aguada Fénix in the MFU pattern, but its form with a west wing exhibits similarity to the VC pattern.

Because of the lack of excavation data regarding VC sites, we chose not to use 'Middle Formative' as a part of the type name. Nonetheless, various lines of evidence suggest that they date to the Middle Formative period, if not earlier. First, the similarity in their morphologies suggests the contemporaneity of MFU and VC complexes. Second, the E Groups of the VC complexes, like those of the MFUs, have a straight eastern platform without superstructures, which are considered to be a temporal marker of the Middle Formative period[2,24,39]. Third, INAH researchers had surveyed 12 VC complexes in southern Veracruz. Although the VC configurations were not always recognized, their investigations confirmed the presence of archaeological sites. At eight of these sites, they surface-collected Formative ceramics, in some cases dating more specifically to the Early or Middle Formative periods (Supplementary Figs. 3–9 and Supplementary Table 5). Fourth, researchers from the Centro INAH Veracruz conducted salvage excavations at the site of El Marquesillo, which may represent a VC complex (Extended Data Fig. 7). Although this site is affected by river cuts and alterations during the later occupation, the lidar image suggests the possibility that its original configuration may have been in the VC pattern. Materials recovered in excavations and surface collections, as well as its Olmec-style throne, suggest that this complex was built during the Early or Middle Formative period[36]. Fifth, most MFU and VC complexes do not have recognizable residential mounds around them, which implies that those complexes were built during the early part of the Middle Formative or earlier, when many groups

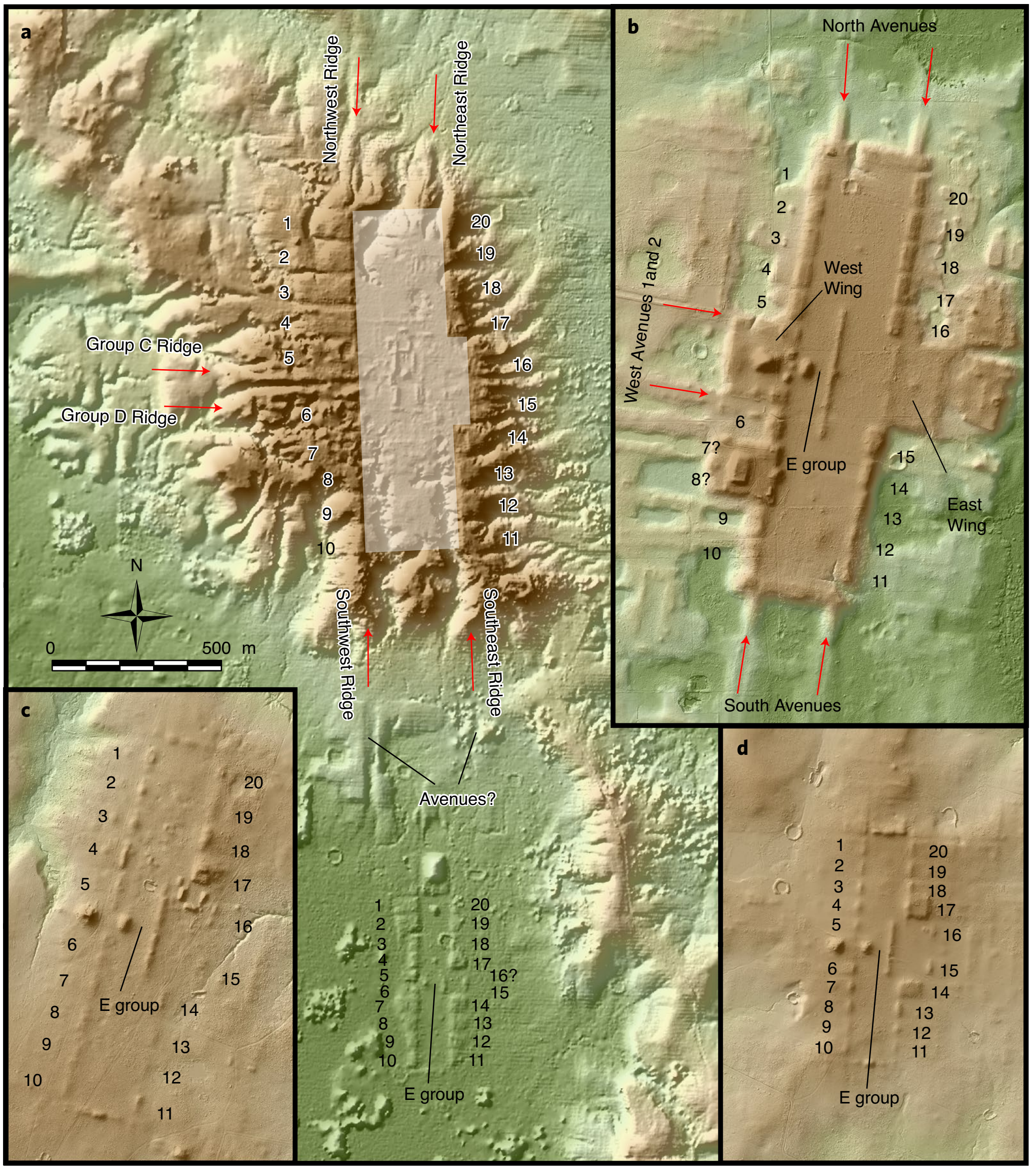


Fig. 4 | Comparison of San Lorenzo and MFUs. All these complexes have rectangular plazas defined by 20 edge platforms. Red arrows indicate the main access ways of San Lorenzo and Aguada Fénix. **a**, San Lorenzo and the south complex. The rectangular flat area of San Lorenzo is indicated in transparent white. (2-m DEM reprocessed from the INEGI lidar.) **b**–**d**, The 0.5-m DEMs derived from the NCALM lidar: Aguada Fénix (**b**); El Macabil (**c**); and Buenavista (**d**).

still lived in post-in-ground structures or other ephemeral buildings without substantial basal platforms (Supplementary Discussion 3 and Supplementary Table 6).

The highest concentration of MFU complexes is in the Middle Usumacinta region, and their distribution extends into the Olmec area. VC complexes are found mostly in southern Veracruz. This pattern suggests that the inhabitants of the Gulf Olmec region and the western Maya lowlands maintained close interactions during the Middle Formative period. MFC and MFG complexes in the study area concentrate in western-central Tabasco and the mountainous area of northwestern Chiapas, possibly along communication routes between La Venta and the Chiapas Grijalva region.

San Lorenzo. The rectangular form of the MFU and VC patterns may have had a direct antecedent in the Olmec centre of San Lorenzo. After the discovery of Aguada Fénix, Inomata et al. pointed out general similarities between this MFU centre and San Lorenzo, whereas Cyphers and Murtha argued that they were different[19,40]. To examine this issue, we reprocessed the INEGI lidar data of San Lorenzo and created an enhanced digital elevation model (DEM). Archaeological maps of San Lorenzo show a series of slightly elevated areas of amorphous shapes on the western and eastern edges of the plateau[16,41]. Our DEM revealed that these features are rectangular platforms, defining a rectangular flat space in the middle (Fig. 4 and Extended Data Fig. 8). We suspect that the differences between the traditional maps and the lidar image resulted from the tendency in ground surveys discussed above to depict large rectangular features in amorphous shapes. San Lorenzo is located where two INEGI lidar swaths overlap, thus providing higher laser shot densities than other areas. Although the lidar image does not correctly show features covered by the tree canopy, in the deforested parts of San Lorenzo there are sufficient ground point densities to accurately represent large cultural features.

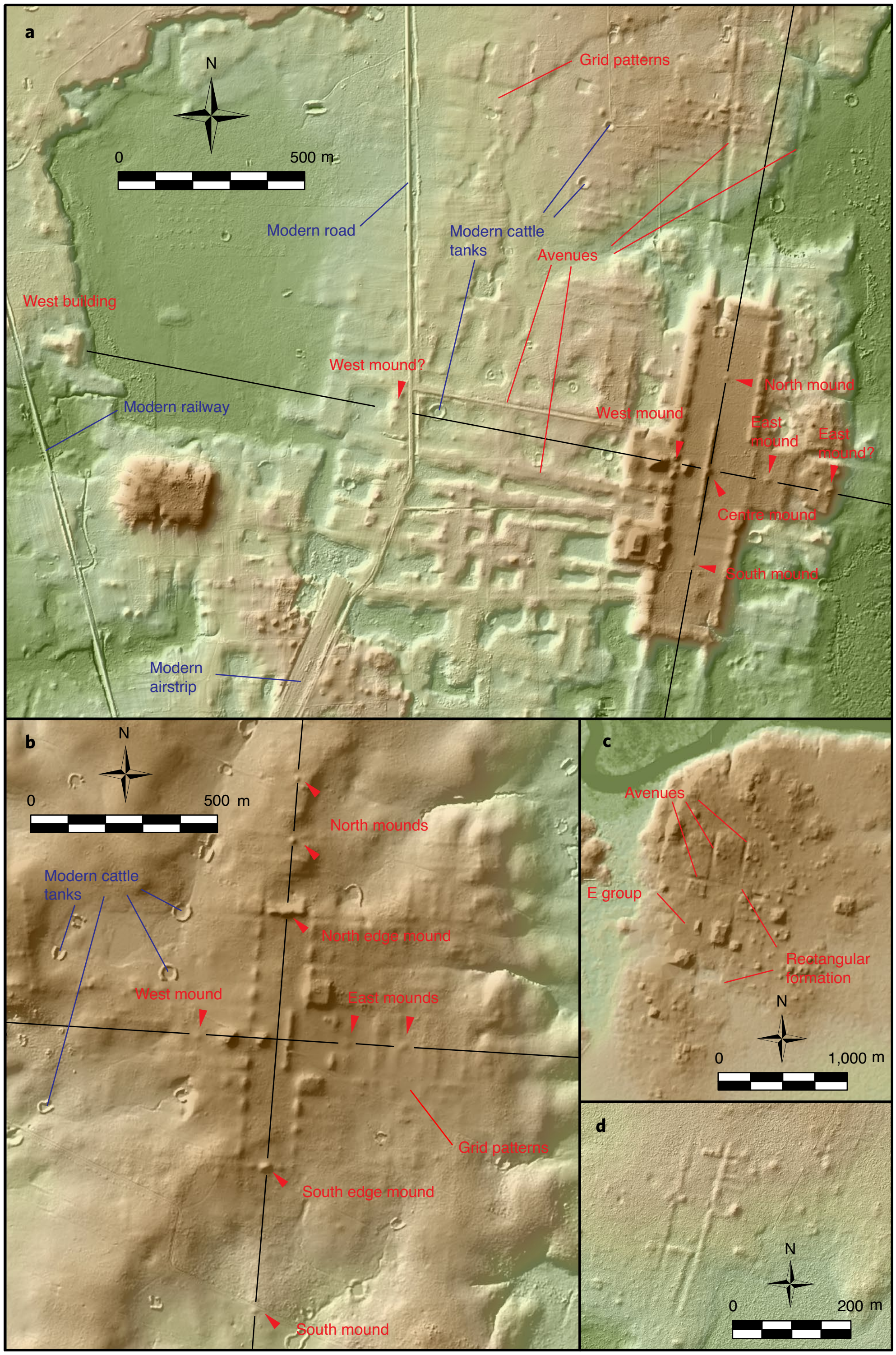


Fig. 5 | Four-directional lines at ceremonial complexes. a, Aguada Fénix (MFU) in the hillshade image of the 0.5-m NCALM DEM. **b**, Buenavista (MFU) in the hillshade of the 0.5-m NCALM DEM. **c**, El Tigre (Primary centre) in the hillshade of the 5-m INEGI DEM. **d**, Los Patitos (minor MFU) with paired north–south corridors in the hillshade of the 0.5-m NCALM DEM.

Scholars agree that the architectural complex in the centre of the San Lorenzo plateau was added during the Villa Alta phase of the Classic period, suggesting that the central area was a flat space during the Formative period. Both traditional archaeological maps and the lidar image show ten edge platforms on each side, thus 20 edge platforms in total. The detailed excavation report by Coe and Diehl shows that the edge platforms were 1–2.5 m higher than the flat area in front of them by the end of the San Lorenzo phase[16] (Supplementary Table 7). In addition, Cyphers and Murtha note that *lagunas* (water-holding depressions) were constructed in modern times as cattle tanks, but otherwise there are no clear indications of conspicuous terrain alterations during the modern period[18]. It is

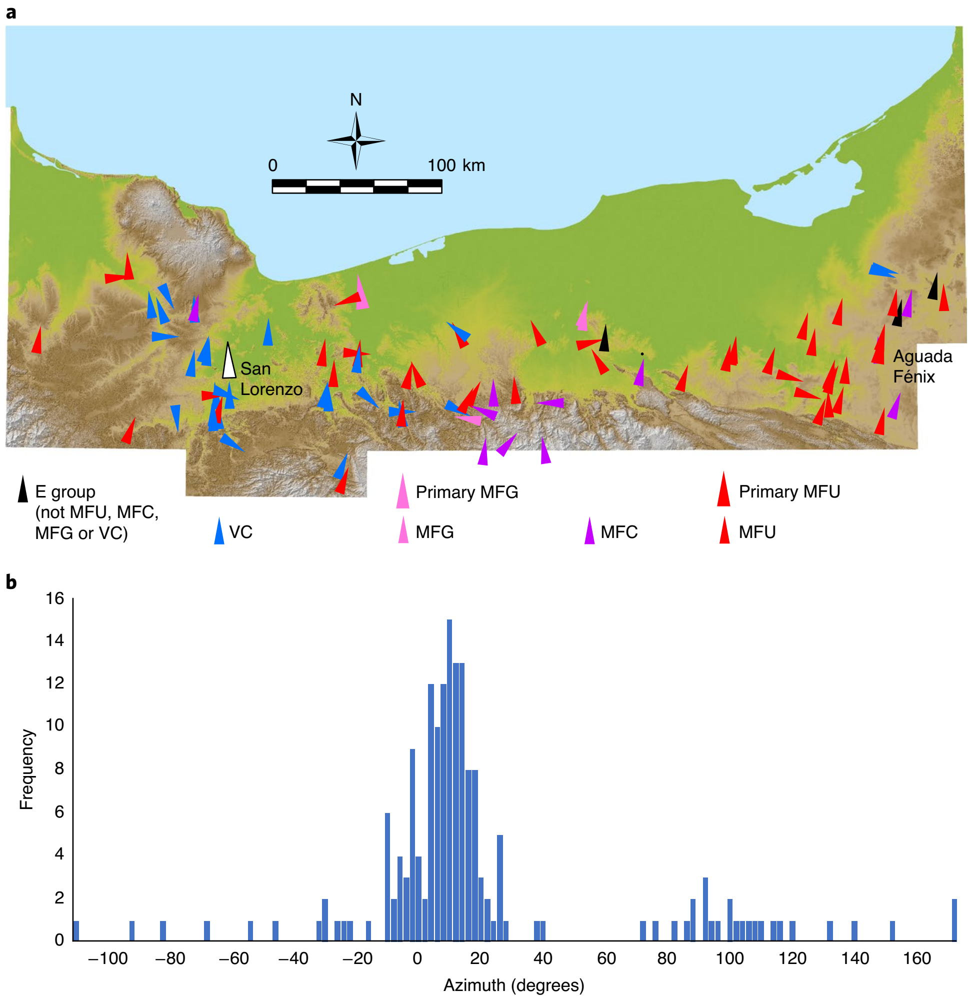


Fig. 6 | Orientations of standardized complexes. a, Orientations of the long axes of standardized complexes or the long platforms of E Groups. The map excludes minor MFUs, minor VCs, rectangular complexes and square complexes. **b**, Histogram of the orientations of all MFUs, VCs, MFCs and MFGs, including primary and minor ones ($n=174$).

likely that the spatial form with edge platforms and the central flat area was formed during the Early Formative apogee of San Lorenzo.

Some MFU sites, including Aguada Fénix and La Duda, exhibit close similarities to the spatial form of San Lorenzo, with 20 rectangular edge platforms separated by narrow alleys. Edge Platforms 15 and 16 of San Lorenzo are offset to the east, creating a space similar to the East Wing of Aguada Fénix. Some MFU complexes, including a previously unknown MFU complex located to the south of the San Lorenzo plateau, also exhibit an identical arrangement of Edge Platforms 15 and 16 (Fig. 4). Excavations by Cyphers uncovered an elite residential complex called the "Red Palace" and a stone sculpture workshop on Edge Platform 5 (Group C Ridge) and a ritual complex called "Group E" (not to be confused with the E Group) in the southern part of Edge Platform 6 (Group D Ridge) and the northern part of Edge Platform 7 (refs. [15,42]). These findings suggest that the area around Edge Platforms 5 and 6 was a focus of elite activity. The west wings of Aguada Fénix and the VC complexes possibly replicated this special area. Other edge platforms at San Lorenzo may have supported residential structures. Cyphers identified a possible residential structure on Edge Platform 14 (Platform D4–7)[17]. The systematic augering programme by Cyphers and colleagues also identified high densities of red and bentonite floors on edge platforms, and they associate those floors with elite residential structures[18,43]. These spatial elements established at San Lorenzo may also have been adopted by MFG complexes, possibly through MFU sites. The MFG centre of La Venta possibly had ten edge platforms on the western side, and the MFG site of Pajonal, a roughly half-size replica of La Venta, appears to have had 20 edge platforms (Fig. 3).

An important question is the use of the rectangular flat space at San Lorenzo. Through their augering programme, Cyphers and colleagues detected red and bentonite floors, although in a lower density than on edge platforms, which suggested to them that there were elite residential complexes in this space[18,43]. This pattern would contrast with the rectangular spaces of Aguada Fénix and other MFU sites, which appear to have been mostly open plazas except for the E Groups. In this case, San Lorenzo and MFU sites may have shared similar overall shapes with a rectangular space defined by edge platforms, but their use of those spaces would have changed substantially. An alternative possibility is that the central area of San Lorenzo was a mostly open plaza without residences as suggested by Diehl[44]. Excavations at Ceibal and other sites show that open plazas at Formative and Classic centres were not necessarily featureless flat spaces but commonly contained low platforms and other subtle features, which were probably used for ritual activities without roofs or with temporary covers[45]. We may consider the possibility that some of the red and bentonite floors in the rectangular space at San Lorenzo were used in similar manners rather than as permanent residences. If so, the spatial form and space use of San Lorenzo and those of Aguada Fénix and other MFU sites would have been remarkably similar, characterized by largely open plazas. This issue needs to be examined with more excavations.

Similarities between San Lorenzo and Aguada Fénix also include their access patterns. At San Lorenzo, the Group C Ridge and Group D Ridge probably served as main access from the west. On the north and south sides, the Northwest Ridge, Northeast Ridge, Southwest Ridge and Southeast Ridge provided ramp-like access ways. The DEM also shows corridor-like features to the south of the San Lorenzo plateau. At Aguada Fénix, West Avenues 1 and 2, the North Avenues and the South Avenues were probably modelled after the access pattern of San Lorenzo (Fig. 4). These access ways at San Lorenzo and Aguada Fénix, as well as the placements of colossal head sculptures along the north–south lines at the former, suggest that processions were important parts of rituals held at those centres[46].

The main difference between San Lorenzo and the MFU, MFG and MFC complexes is the absence of an E Group and pyramidal structures at the former. Earlier pyramidal structures are found on the Pacific Coast of Chiapas and Guatemala[47]. There, the site plan of Ojo de Agua, dating to the Jocotal phase (1,200–1,000 BC), appears to represent a prototype of the E Group and the MFC pattern[48]. MFC complexes located in central Chiapas have more spacious placements of platforms than the MFG pattern and are similar to the earlier and contemporaneous sites on the Chiapas–Guatemala Pacific Coast, including Ojo de Agua, Tzutzuculi and Izapa[5,20,48]. The MFC pattern with an E Group may have spread from the Pacific Coast to central Chiapas and other areas[49]. These observations suggest that the MFU pattern represents a mix of the traditions originating from San Lorenzo and the Pacific Coast with local innovations. La Venta and other MFG complexes also appear to have merged elements from various regions. They followed the main format of the MFC pattern, but their neatly aligned edge platforms, in some cases with 20 of them, possibly derived from San Lorenzo and the MFU complexes.

Calendrical and directional symbolisms. The 20 edge platforms found at San Lorenzo, Aguada Fénix, Buenavista, El Macabil, Pajonal and other sites probably represent the base unit of Mesoamerican calendars and the vigesimal numerical system of the region. These buildings are subdivided into groups of ten (on each side) and then those of five (northern and southern ones on each side). The subdivision of 20 years into 10- and 5-year units formed the primary structure in the Maya Long Count calendar and shaped ritual cycles. D. Stuart (personal communication) also pointed out to Inomata that the division of 20 into four groups of five probably relates to the Mesoamerican concept of year-bearers. In the Mesoamerican Calendar Round system, the day in the 260-day calendar corresponding to the beginning of a 365-day calendar year is called the year-bearer of that year. Four 260-day calendar day names rotate in a 4-year cycle, thus the 20 days forming the 260-day calendar are divided into four groups of 5 days in this system[50–52].

The orientations of standardized complexes may also represent directional symbolisms tied to cosmological views and ritual practices. At the MFU sites of Aguada Fénix and Buenavista, the north–south and east–west directions are marked by lines of small mounds, in addition to the E Groups (Fig. 5). Those sites are among the many Formative complexes in our study area that are oriented between −10° and 30° in azimuths (Fig. 6). Similar orientations are also observed among E Group assemblages in the Maya lowlands, dating from the Middle Formative to the Early Classic[2,39,53–55]. Both among the Formative complexes in our study region and E Groups in the Maya lowlands, the highest frequencies are found around 11° or 12° for the north–south axes (101° or 102° for the east–west axes). Aveni and colleagues have argued that these orientations correspond to the sunrise on a specific calendar date (19 February), which precedes the solar zenith passage date (10 May) by 80 days (4 × 20 days)[56]. They also have noted that other common directions of E Groups correspond to dates separated from the zenith passage date by 3 × 20 days (11 March) and 2 × 20 days (31 March). The east–west axis of Aguada Fénix, for example, is aligned to the sunrise during 17–24 February (a range due to slight offsets among mounds) and that of Buenavista on 12 or 13 March. Aveni and colleagues and other scholars have suggested that these dates represent the 260-day Maya agricultural calendar[55–57]. If these interpretations are correct, some complexes in our study region may represent some of the earliest manifestations of this symbolism.

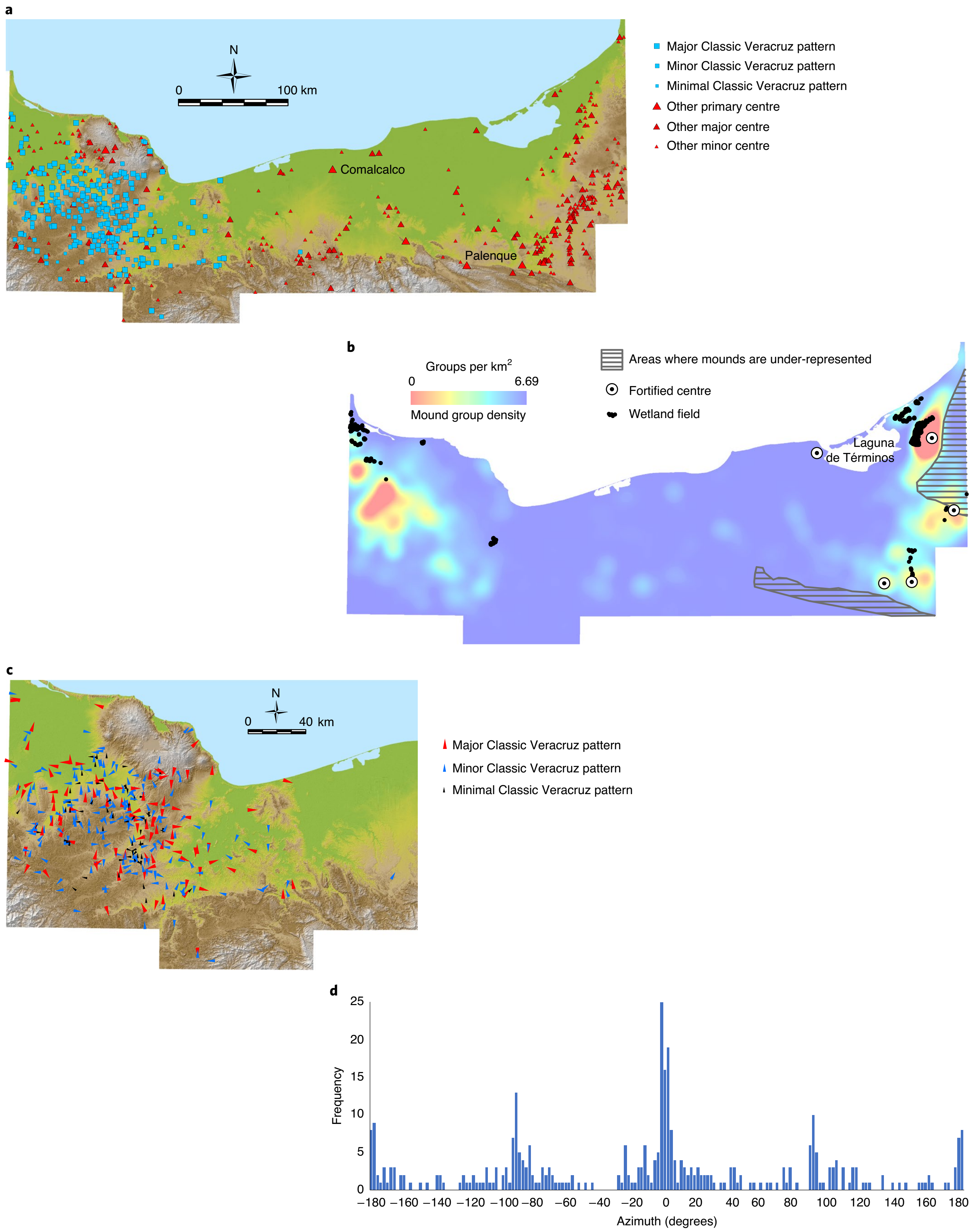
In designing ceremonial complexes, the builders of Aguada Fénix and Buenavista appear to have laid out orthogonal lines first, according to which they constructed multiple rectangular complexes and avenues. If so, their directional symbolism may have been tied to the forms of ritual processions that were carried out there. A similar procedure may have been used at some MFG complexes, with parallel lines defined by the front faces of the edge platforms serving as the basis of the site plan and possible procession routes. An intriguing case is the site of El Tigre. There, two parallel north–south lines, which E. Vargas Pacheco calls *caminos*, are cut through elevated parts of the terrain[37]. With east–west lines, they make a rectangular layout of the site (Fig. 5). Although many buildings at El Tigre date to later periods, these lines may reflect the original design of the site comparable to the MFU pattern. At some smaller complexes, two parallel lines may also have been used as the basis for the site layout and as procession routes (Fig. 5).

There is, however, a substantial number of complexes that do not fit orientations tied to the zenith passage date, particularly in mountainous areas. In some cases, complexes appear to have been placed in whatever directions fitted limited flat terrains. In southern Veracruz, some complexes are aligned to high peaks in the Tuxtla Mountains. Alignments to high mountains and volcanoes are also found in Formative complexes in central Chiapas and on the Pacific Coast[49,58,59]. These patterns suggest that the Formative people designed their ritual spaces by selectively using various cosmological principles and adjusting them to local conditions.

Later periods. Various survey projects suggest that before 400 BC mounded settlements are scarce in our study area outside the standard ceremonial complexes[60–63]. Settlements of the Classic period, particularly the Late Classic, probably make up a substantial part of small mounded groups. In the eastern part of our study area, Palenque and its surroundings had a population peak during the Late Classic period. Their demographic levels during the Late-Terminal Formative, Early Classic and Post-Classic periods were substantially smaller[64,65]. The Candelaria River region and the area around the Laguna de Términos appear to have had a considerable number of Late and Terminal Formative and Post-Classic sites,

Fig. 7 | Sites dating to later periods. a, Locations of centres of later periods, showing the distributions of different types of complexes in southern Veracruz and the Maya lowlands. We suspect that many of them, particularly Classic Veracruz complexes, date to the Classic period. Only complexes identified in the INEGI lidar are plotted. **b**, Densities of mound groups of later periods. High densities in the Maya lowlands are associated with fortified centres and wetland fields, particularly in the area east of the Laguna de Términos. Mound densities in the hatched areas are under-represented in the INEGI lidar. Only mound groups identified in the INEGI lidar were used. Some wetland data are from refs. [27,78]. **c**, Orientations of Classic Veracruz complexes. **d**, Histogram of Classic Veracruz complexes by their azimuths ($n = 366$).

but Classic-period occupation was still a major component[37,66,67]. In southern Veracruz, many mound complexes can be more securely dated to the Late and Terminal Classic periods (AD 600–1,000) because of their characteristic arrangements. Each of these complexes consists of elongated mounds flanking a plaza and conical mounds or pyramids on one or two ends. These complexes have



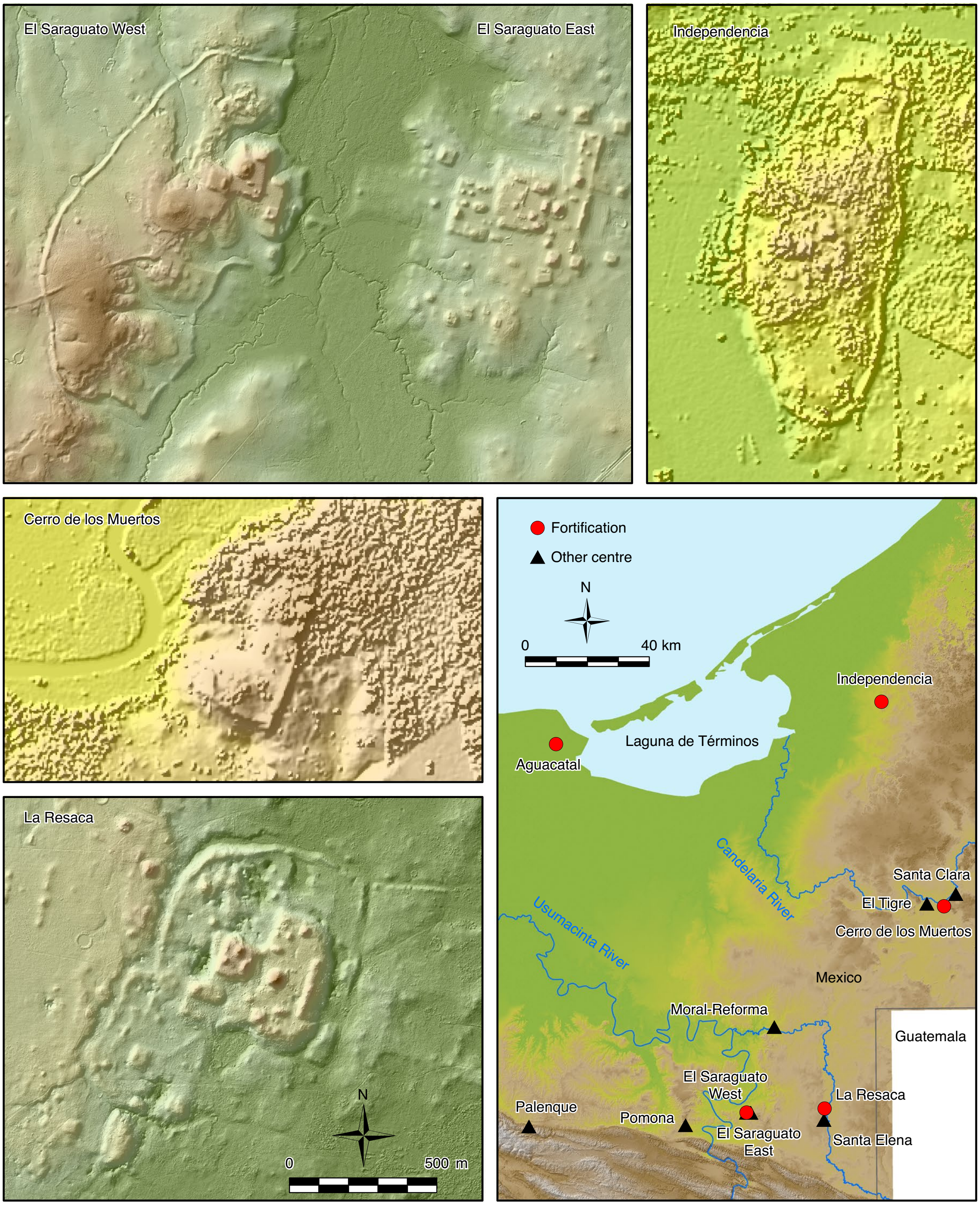


Fig. 8 | Fortified sites in the Maya area. The images of the sites are shown on the same scale. Each of the fortified sites is located near other centres: El Saraguato West (NCALM DEM) near El Saraguato East; Independencia (INEGI DSM) near multiple major and minor centres; Cerro de los Muertos (INEGI DSM) between El Tigre and Santa Clara; and La Resaca (NCALM DEM) near Santa Elena. Aguacatal is not clearly visible in the INEGI lidar because of dense vegetation.

been called the Long-Plaza Plan, the Villa Alta Quadripartite Arrangement or Tipo 4 (refs. [61,62,68–75]). To avoid confusion with the Formative standardized complexes with rectangular plazas, here we call them the Classic Veracruz pattern. There are some post-Classic settlements in southern Veracruz, but a review of data suggests that many regions experienced 72–100% population declines from the Classic to post-Classic periods[76].

Given their chronological uncertainties, we only make some general observations on the distribution pattern of mounded groups other than the Formative standardized complexes. The close interaction across the study area appears to have broken down, possibly after the decline of La Venta and some MFC sites around 400 BC (Fig. 7). The high densities of probable later mounded sites are found in the western Maya lowlands and southern Veracruz, whereas their densities in western and central Tabasco are low. A previous study using the INEGI lidar and other remotely sensed data by Stoner and colleagues shows that some complexes in southern Veracruz are associated with wetland agricultural fields[27,28]. The orientations of Classic Veracruz complexes tend to concentrate around true north and other cardinal directions, although there are also substantial deviations from this norm (Fig. 7). Whereas some Classic Veracruz complexes appear to have been aligned to peaks in the Tuxtla Mountains, a substantial number of them may have been tied to the solar cycle, emphasizing the equinox and solstice sunrise directions[70,74].

In the Maya area, later mound groups concentrate on the karstic uplands near the eastern edge of the study area. In addition to the well-known wetland fields near El Tigre in the Candelaria drainage[37,77], the NCALM lidar revealed a series of wetland fields along the San Pedro River (Fig. 7). A surprising result is the extremely high mound density in the area east of the Laguna de Términos, associated with the possibly most extensive wetland field system in the Maya lowlands[78]. These results highlight the importance of wetland field systems in the Maya lowlands[21,79]. Five fortified centres surrounded by walls or dry moats exist in the eastern part of the study area (Fig. 8). Among them, Aguacatal, La Resaca and Cerro de los Muertos date primarily to the Classic period[37,80–82]. To our knowledge, Independencia and El Saraguato West were not previously reported. These finds accord with increasing studies that suggest the prevalence of war in Maya society[21,83–93]. These fortifications, with the possible exception of Aguacatal, are found close to other unfortified centres. These patterns may reflect the practice of war by the Maya, in which the residents of nearby areas took refuge in those fortifications during attacks[21].

Discussion

Our finds potentially push back the origins of standardized spatial formats and the manifestations of calendrical and directional symbolisms in built forms to the heyday of San Lorenzo between 1,400 and 1,150 BC. Between 1,050 and 750 BC, or possibly earlier, the MFUs and VCs most likely bridged San Lorenzo and later site plans, including the MFG pattern of La Venta. The Middle Usumacinta region with the centre of Aguada Fénix possibly played an important role in formalizing the rectangular configuration. At the same time, the identification of MFU and VC complexes throughout the Gulf Olmec region encourages us to examine the continued participation of the Gulf Olmecs in this process. These observations highlight the role of San Lorenzo in developing spatial concepts and symbolisms while emphasizing the importance of complex inter-regional interactions during the following periods.

Our continued research confirmed the initial results from Aguada Fénix that there is substantial diversity in various aspects of society in the study area, despite the shared architectural configurations. First, the ceramics of 1,200 to 750 BC in the Middle Usumacinta region closely resemble those of the central and southwestern Maya lowlands and lack characteristic vessels of the Olmec region[19]. Ceramic styles should not be equated with ethnic or linguistic identities, and we are not suggesting that the inhabitants of the Middle Usumacinta region during this period were Mayan language speakers. Nonetheless, these ceramics imply that the builders of Aguada Fénix and nearby complexes maintained close interaction with communities in the central and southwestern Maya lowlands. Second, around many MFU and VC complexes, there were not many substantial residential buildings that are recognizable in lidar. The inhabitants of those areas may have lived in ephemeral structures, moving seasonally or every few years according to the seasonal use of natural resources or swidden agriculture cycles (Supplementary Discussion 3). This pattern contrasts with the presence of substantial permanent residences at San Lorenzo[42]. Third, the levels of social inequality and political centralization may have varied. Colossal head sculptures at San Lorenzo and La Venta suggest the presence of centralized polities with rulers, whereas we have not found evidence of marked social inequality in the Middle Usumacinta region between 1,200 and 750 BC. Those diverse populations were probably tied through shared ritual practices and cosmologies as reflected in the standardized spatial formats.

Standardized complexes are rare in the Maya lowlands east of our study area. In addition to the MFC site of Ceibal, an important exception is the Middle Formative site of Nixtun-Ch'ich', which has parallel east–west and north–south corridors like those at San Lorenzo and Aguada Fénix[12,94]. Many Maya sites began to adopt E Groups around 700 BC or later but they did not integrate other elements of the MFU and MFC patterns. Although E Groups have often been considered characteristic features of the Maya lowlands, these data indicate that the greater Isthmian area, extending from the western Maya lowlands to Chiapas and southern Veracruz, was the primary area for the initial development of the E Group as a central component of standardized site plans[49].

These interpretations need to be tested and refined through future research. Still, the broad distribution of standardized complexes compels us to examine the role of those sites and interactions among them in the initial development of Mesoamerican cultural traits, including calendars, cosmologies and building styles.

Methods

Lidar datasets. We first identified MFU complexes in the high-resolution lidar that we obtained in collaboration with the NCALM in 2017 and 2019. This lidar data covered an area of 1,015 km^2 and digital elevation models (DEMs: ground surface models without vegetation and modern buildings) and digital first surface models (DSMs: models with vegetation and buildings) were created at horizontal spacings of 1 m (2017 data) and 0.5 m (2019 data). The NCALM has been collecting substantial lidar data in Mesoamerica in collaboration with archaeologists[21–24,95–103]. The NCALM lidar provided detailed information on multiple ceremonial complexes. We then expanded our analysis of ceremonial complexes by examining the INEGI lidar. The INEGI lidar data were designed to generate terrain relief data for the National System of Statistical and Geographical Information for diverse needs throughout Mexico. The INEGI produced DEMs and DSMs at a horizontal spacing of 5 m and made them publicly available (https://inegi.org.mx). Cyphers and colleagues previously examined the INEGI lidar for the area of San Lorenzo[41,104]. We reprocessed INEGI point clouds for areas around San Lorenzo and Pajonal. The INEGI provided unclassified, unfiltered point clouds for those areas. We classified points through the "class as ground" routine in TerraScan software v.20.04, using loose parameters. Because of the low return density, we had to manually clean and correct some vegetation returns for important areas. We then produced DEMs at a horizontal grid spacing of 2 m using a kriging interpolation algorithm implemented in Surfer v.16.

To examine the effectiveness of the INEGI lidar in identifying archaeological features, we compared it with the NCALM lidar and two other high-resolution lidar datasets (Fig. 1 and Supplementary Table 1). One is NASA Goddard's Lidar, Hyperspectral and Thermal Imager (G-LiHT) and the other is a dataset acquired by the Centro del Cambio Global y la Sustentabilidad (CCGS), Tabasco. The G-LiHT lidar data were originally intended for environmental studies[105,106] and NASA made the point clouds, 1-m horizontal resolution DEMs and other data publicly available (https://gliht.gsfc.nasa.gov/). We also improved the ground classification of the G-LiHT point clouds for our study area and produced enhanced 1-m-resolution DEMs. The CCGS collected its lidar data for the study of wetland ecology on the western shore of the Laguna Colorada. In a collaboration between the CCGS and our project, we exchanged our lidar data.

Lidar data analysis. We manually plotted archaeological features by examining different lidar data visualizations, including hillshade and Red Relief Image Map (RRIM)[103,107,108]. We are currently in the process of developing an automated site detection involving machine learning algorithms, but many scholars agree that the identification of sites by trained experts is still the most effective method[29,30,109]. We plotted individual monumental complexes of civic or ceremonial nature (MFUs, MFCs, MFGs, VCs, Classic Veracruz pattern and other centres) and collected their attribute information (orientation, length, width, mound height and so on), using ArcGIS 10.7.1 and QGIS 3.10.2. In addition, we plotted small mound groups, most of which were probably residential groups. We also reviewed data from the systematic surveys shown in Fig. 1c, as well as other reconnaissance data[37,60,110–116]. We, however, did not plot sites when their exact locations could not be identified in lidar images.

To record the orientations of complexes with an E Group, we measured the angles of their long axes from the UTM N 15 grid north. In these measurements, the E Group pyramid was placed on the left side of the observer facing the orientation of the complex on its long axis. Although most E Groups have their pyramids on the west side, there are cases in which the pyramids are found on the north, south or east sides. For VCs without an E Group, we measured the orientation of their long axes with the better-defined wings on the left side of the observer facing the orientation of the complex. For a Classic Veracruz complex, the orientation was defined as the direction from the shorter end structure toward the taller end pyramid along the main axis parallel to the long lateral mounds. These angle measurements were then converted to azimuths from true north by subtracting the grid convergence angles (angle between true north and the UTM grid north). Figures 6a and 7c are plotted with angles from the UTM grid north, whereas the histograms in Figs. 6b and 7d are based on azimuths from true north. The length and width of a complex were measured between the outer edges of mounds defining the complex.

To ensure consistency in the identification of archaeological features, Inomata first analysed the INEGI, NCALM, G-LiHT and CCGS data of the entire area, primarily examining DEMs and RRIMs, and plotted archaeological complexes and mound groups. M.G.M. then reanalysed the INEGI lidar of the entire area, examining DEMs and DSMs, and added more archaeological features, which Inomata verified and included in the database. Although we did not systematically test the variability in site detection between researchers, we think that the difference is small. Those added by M.G.M. were mostly filtered out in DEMs but were better visible in DSMs. T.I. examined the attribute data of Formative standardized complexes and M.G.M. and F.P. collected the attribute data of Classic Veracruz complexes. M.G.H. measured building heights of major and minor centres.

Effectiveness and limitations of the INEGI lidar. To evaluate the effect of vegetation on the INEGI lidar, we produced a Canopy Height Model (CHM) raster, by subtracting the INEGI DEM from the INEGI DSM (Fig. 1c and Supplementary Table 2). The values of individual cells of the CHM indicate the height of vegetation: low values indicate open fields or pastures and high values reflect tall forests. In areas with pastures or sparse vegetation, the INEGI's 5-m-resolution DEMs effectively show mounds lower than 1 m. In some parts of the INEGI DEMs, however, structures visible in DSMs are filtered out. In the 2-m-resolution DEMs that we reprocessed, those structures are clearly visible.

In areas covered by dense vegetation, the INEGI lidar hardly penetrated the canopy and even large structures are difficult to identify. A particularly problematic area is the Campeche hill region (Fig. 1c). The G-LiHT Transects 5 and 6 show that there exist dense settlements in this area, but vegetation inhibits the detection of most of them in the INEGI lidar (Supplementary Discussion 1 and Supplementary Fig. 2). The Chiapas and Oaxaca Mountains also represent difficult conditions. In particular, the northeastern edge of the Chiapas Mountains, which may be called the Palenque–Chinikiha zone, is known to have important centres, including Palenque and Chinikiha[64]. Most settlements associated with these centres cannot be identified in the INEGI lidar. In other rugged terrains of the Chiapas and Oaxaca Mountains, the densities of sites are probably low, as suggested by G-LiHT Transects 1 and 2 (Supplementary Table 3). Many settlements in these areas were probably concentrated in valleys. Many of the valleys are now substantially deforested, and it is often possible to identify archaeological features in the INEGI lidar. Likewise, the high elevation parts of the Tuxtla Mountains are covered by forests, but previous ground surveys suggest that most settlements in this region are found in valleys and foothills[117,118]. Dense vegetation is also found in coastal regions. Some major sites in these parts, including Aguacatal, Xicalango and El Bellote, are not visible in the INEGI lidar[80,119,120]. Many archaeological sites in these regions appear to concentrate on beach ridges and levees along rivers and old channels, and settlement densities in poorly drained parts of mangroves and coastal wetlands were probably low. No archaeological features were recognized in the CCGS lidar covering a coastal wetland (Supplementary Table 3).

A large part of the study area has little or low vegetation with a patchy distribution of medium to high vegetation. Under these conditions, verification with the NCALM lidar shows that substantial portions of large complexes (91% of MFUs, 100% of MFCs and 80% of major rectangular complexes) are identified in the INEGI lidar (Supplementary Table 3). This result suggests that the distribution pattern of large complexes in the study area obtained from the INEGI lidar presents valuable archaeological information. The accuracies of identification for smaller complexes, including minor MFUs, minor centres, minor rectangles and square complexes, are lower, ranging from 45 to 64%. The detection accuracies for smaller mound groups vary from 18 to 58%. This variability suggests that the detection rates of sites are strongly affected by the distribution patterns of vegetation patches. We should be cautious in using the INEGI lidar in comparing site densities among small areas because site density estimates may be considerably lower than reality in areas with dense vegetation covers. On larger spatial scales, however, average ratios of deforested to forested areas are similar across different areas (Fig. 1c), and thus data obtained from the INEGI lidar provide useful information on the overall distribution of archaeological features, including small mound groups (again, except for the dense vegetation areas of the Oaxaca–Chiapas Mountains, Campeche hills and coastal ridges and wetlands). For example, the highest density of mound groups is found in an area east of the Laguna de Términos (Fig. 7b), despite the relatively extensive forest coverage in the area (Fig. 1c). This observation indicates that the identification of this high-density area, as well as those of other areas of high mound densities, is valid.

The central portion of the study area had important Early and Middle Formative sites, but many sites of these periods probably did not have highly visible mounds. Previous ground surveys in these regions suggest that densities of mounded sites were relatively low[60,62,63,121,122]. This observation is also supported by the analysis of the G-LiHT Transect 2, which did not reveal many mounded sites in the alluvial plains of the Uspanapa River in southeastern Veracruz.

Pedestrian surveys. The MUAP conducted the field validation of eight MFUs and MFCs, including Aguada Fénix, the Northwest Plaza of Aguada Fénix, La Carmelita, El Tiradero, Buenavista, El Macabil, El Saraguato, Rancho Zaragoza, El Cacho, Savocoche, El Marino, El Mirador and Chrisóforo Chiñas. In addition, we ground-truthed 14 minor MFUs, 14 minor rectangles, four square complexes and 17 minor centres. All these complexes were verified to be archaeological sites.

The Centro INAH Veracruz conducted systematic ground surveys in southern Veracruz from 2006 through 2014 under the direction of Lourdes Hernández Jiménez. This research was carried out as salvage operations associated with the petroleum prospection conducted by PEMEX-COMESA. INAH archaeologists followed the oil prospection transects, which were laid in parallel or grid patterns with spacings ranging between 150 m and 5 km. They expanded their reconnaissance to areas between transects as necessary. When archaeological sites were found, they mapped them and collected artefacts found on the ground. In this research conducted before our lidar analysis, INAH investigators noted the presence of extensive plazas at various sites but the degree of their standardization was not fully recognized. This is mainly because these horizontally extensive complexes defined by low mounds are extremely difficult to recognize from the ground level. Among the sites classified as MFCs, MFUs, VCs, rectangles and squares in our lidar analysis, 47 were confirmed to be archaeological sites, some with Formative components, by INAH researchers.

Excavations. The MUAP carried out excavations at Aguada Fénix, El Tiradero, La Carmelita, Buenavista and Rancho Zaragoza. The operations at Aguada Fénix and La Carmelita before 2020, along with their methods, are described in ref. [19]. In 2020, we carried out Operation (Op.) NR5B, a $4\times4\,m^2+2\times3\,m^2$ excavation along the east–west axis of the Aguada Fénix E Group plaza; Op. NR7C, a $4\times1.5\,m^2$ trench on the eastern side of Edge Platform 18 of the Aguada Fénix plateau; and Op. NR9A, a $2\times2\,m^2$ unit on the northern altar-like mound of the Aguada Fénix plateau. We also conducted Op. AF1D, an $8\times2\,m^2+6\times2\,m^2$ excavation in an Aguada Fénix peripheral group. Excavations at El Tiradero involved the cleaning of a modern cut (Op. TR1) and two $4\times4\,m^2$ units along the east–west axis in the E Group plaza (Ops. TR2A and TR2B). At Buenavista, we excavated two $2\times2\,m^2$ units along the east–west axis of the E Group (Ops. BV1A and BV1B). At Rancho Zaragoza, we placed one $2\times2\,m^2$ unit (Op. ZR1A) along the east–west axis of the E Group and another $2\times2\,m^2$ unit (Op. ZR1B) on the western side of the E Group.

Reporting Summary. Further information on research design is available in the Nature Research Reporting Summary linked to this article.

Data availability

The database of archaeological sites identified in this study is available at the University of Arizona Campus Repository (https://repository.arizona.edu/handle/10150/659895)[123].

Code availability

The Oxcal code used for Bayesian analysis is provided in Supplementary Information.

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References

1. Fash, W. L. & López Luján, L. *Art of Urbanism: How Mesoamerican Kingdoms Represented Themselves in Architecture and Imagery* (Dumbarton Oaks Research Library and Collection, 2009).
2. Freidel, D. A., Chase, A. F., Dowd, A. S. & Murdock, J. *Maya E Groups: Calendars, Astronomy, and Urbanism in the Early Lowlands* (Univ. Press of Florida, 2017).
3. Clark, J. E. & Hansen, R. D. in *Royal Courts of the Ancient Maya* Vol. 2 (eds Inomata, T. & Houston, S. D.) 1–45 (Westview, 2001).
4. Lowe, G. W. in *The Origins of Maya Civilization* (ed. Adams, R. E. W.) 197–248 (Univ. of New Mexico Press, 1977).
5. McDonald, A. J. *Tzutzuculi: A Middle-Preclassic Site on the Pacific Coast of Chiapas, Mexico* (New World Archaeological Foundation, Brigham Young Univ., 1983).
6. Lee, T. A. & Clark, J. E. *Chiapa de Corzo, Mound 17: Comparative Analysis of a Salvage Excavation* (Brigham Young Univ., 2016).

7. Bachand, B. R. & Lowe, L. S. in *Arqueología Reciente de Chiapas: Contribuciones del Encuentro Celebrado en el 60° Aniversario de la Fundación Arqueológica Nuevo Mundo* Papers of the New World Archaeological Foundation No. 72 (eds Lowe, L. S. & Pye, M. E.) 45–68 (Brigham Young Univ., 2012).
8. Drucker, P., Heizer, R. F. & Squier, R. H. *Excavations at La Venta, Tabasco, 1955* (Smithsonian Institution, 1959).
9. Lowe, G. W. in *The Olmec and Their Neighbors* (eds Coe, M. D. & Grove, D.) 231–256 (Dumbarton Oaks Research Library and Collection, 1981).
10. Estrada-Belli, F. *The First Maya Civilization: Ritual and Power Before the Classic Period* (Routledge, 2011).
11. Clark, J. E. in *The Origins of Maya States* (eds Traxler, L. P. & Sharer, R. J.) 123–224 (Univ. of Pennsylvania Museum of Archaeology and Anthropology, 2016).
12. Inomata, T., Triadan, D., Aoyama, K., Castillo, V. & Yonenobu, H. Early ceremonial constructions at Ceibal, Guatemala, and the origins of lowland Maya civilization. *Science* **340**, 467–471 (2013).
13. Inomata, T. & Triadan, D. Middle Preclassic Caches from Ceibal, Guatemala. *Maya Archaeol.* **3**, 56–91 (2016).
14. Blomster, J. P., Neff, H. & Glascock, M. D. Olmec pottery production and export in ancient Mexico determined through elemental analysis. *Science* **307**, 1068–1072 (2005).
15. Cyphers, A. & Di Castro, A. in *Art of Urbanism: How Mesoamerican Kingdoms Represented Themselves in Architecture and Imagery* (eds Fash, W. L. & López Luján, L.) 21–52 (Dumbarton Oaks Research Library and Collection, 2009).
16. Coe, M. D. & Diehl, R. A. *In the Land of the Olmec* (Univ. of Texas Press, 1980).
17. Cyphers, A. *Población, Subsistencia y Medio Ambiente en San Lorenzo Tenochtitlan* (Universidad Nacional Autónoma de México, 1997).
18. Cyphers, A. & Murtha, T. in *Mesoamerican Plazas: Arenas of Community and Power* (eds Tsukamoto, K. & Inomata, T.) 71–89 (Univ. of Arizona Press, 2014).
19. Inomata, T. et al. Monumental architecture at Aguada Fénix and the rise of Maya civilization. *Nature* **582**, 530–533 (2020).
20. Rosenswig, R. M. & López-Torrijos, R. Lidar reveals the entire kingdom of Izapa during the first millennium BC. *Antiquity* **92**, 1292–1309 (2018).
21. Canuto, M. A. et al. Ancient lowland Maya complexity as revealed by airborne laser scanning of northern Guatemala. *Science* **361**, eaau0137 (2018).
22. Chase, A. F. et al. Airborne LiDAR, archaeology, and the ancient Maya landscape at Caracol, Belize. *J. Archaeol. Sci.* **38**, 387–398 (2011).
23. Chase, A. F. et al. Ancient Maya regional settlement and inter-site analysis: the 2013 west-central Belize LiDAR Survey. *Remote Sens.* **6**, 8671–8695 (2014).
24. Inomata, T. et al. Archaeological application of airborne LiDAR to examine social changes in the Ceibal region of the Maya lowlands. *PLoS ONE* **13**, e0191619 (2018).
25. Crutchley, S. in *Laser Scanning for the Environmental Sciences* (eds Heritage, G. L. & Large, A. R. G.) 180–200 (Blackwell Publishing, 2009).
26. Howey, M. C. L., Sullivan, F. B., Burg, M. B. & Palace, M. W. Remotely sensed big data and iterative approaches to cultural feature detection and past landscape process analysis. *J. Field Archaeol.* **45**, S27–S38 (2020).
27. Stoner, W. D. Risk, agricultural intensification, political administration, and collapse in the classic period gulf lowlands: a view from above. *J. Archaeol. Sci.* **80**, 83–95 (2017).
28. Stoner, W. D., Stark, B. L., VanDerwarker, A. & Urquhart, K. R. Between land and water: hydraulic engineering in the Tlalixcoyan basin, Veracruz, Mexico. *J. Anthropol. Archaeol.* **61**, 101264 (2021).
29. Casana, J. Global-scale archaeological prospection using CORONA satellite imagery: automated, crowd-sourced, and expert-led approaches. *J. Field Archaeol.* **45**, S89–S100 (2020).
30. Wernke, S., VanValkenburgh, P. & Saito, A. Interregional archaeology in the age of big data: building online collaborative platforms for virtual survey in the Andes. *J. Field Archaeol.* **45**, S61–S74 (2020).
31. Inomata, T., Triadan, D., Pinzón, F. & Aoyama, K. Large plateau construction during the Preclassic period at the Maya site of Ceibal, Guatemala. *PLoS ONE* **14**, e0221943 (2019).
32. Willey, G. R., Smith, A. L., Tourtellot III, G. & Graham, I. *Excavations at Seibal, Department of Peten, Guatemala: Introduction: The Site and its Setting* (Harvard Univ., 1975).
33. Lowe, G. W., Lee, T. A. & Martînez E., E. *Izapa: An Introduction to the Ruins and Monuments* (Brigham Young Univ., 1982).
34. Rosenswig, R. M., López-Torrijos, R., Antonelli, C. E. & Mendelsohn, R. R. Lidar mapping and surface survey of the Izapa state on the tropical piedmont of Chiapas, Mexico. *J. Archaeol. Sci.* **40**, 1493–1507 (2013).
35. Anaya Hernández, A. *The Pomoná Kingdom and its Hinterland* (FAMSI, 2002).
36. Doering, T. F. *An Unexplored Realm in the Heartland of the Southern Gulf Olmec: Investigations at El Marquesillo, Veracruz, Mexico* (Univ. of South Florida, 2007).
37. Vargas Pacheco, E. *Itzamkanac, El Tigre, Campeche: Exploración, Consolidación y Análisis de los Materiales de la Estructura 1* (Universidad Nacional Autónoma de México, 2013).
38. Miller, D. E. *Excavations at La Libertad, a Middle Formative Ceremonial Center in Chiapas, Mexico* (Brigham Young Univ., 2014).
39. Aimers, J. J. & Rice, P. M. Astronomy, ritual, and the interpretation of Maya "E-group" architectural assemblages. *Anc. Mesoam.* **17**, 79–96 (2006).
40. Cyphers, A. & Murtha, T. Mayas y olmecas: nuevas perspectivas. *Arqueología Mexicana* **28**, 78–81 (2020).
41. Cyphers, A., Murtha, T. & Zurita, J. *Atlas Digital de la Zona Arqueológica de San Lorenzo, Veracruz* (Instituto de Investigaciones Antropológicas, 2014).
42. Cyphers, A. in *The Origins of Maya States* (eds Traxler, L. P. & Sharer, R. J.) 83–122 (Univ. of Pennsylvania Museum of Archaeology and Anthropology, 2016).
43. Arieta Baizabal, V. & Cyphers, A. Densidad poblacional en la capital olmeca de San Lorenzo, Veracruz. *Anc. Mesoam.* **28**, 61–73 (2017).
44. Diehl, R. A. *The Olmecs: America's First Civilization* (Thames & Hudson, 2004).
45. Tsukamoto, K. & Inomata, T. *Mesoamerican Plazas: Practices, Meanings, and Memories* (Univ. of Arizona Press, 2014).
46. Grove, D. C. in *Social Patterns in Pre-Classic Mesoamerica* (eds Grove, D. C. & Joyce, R. A.) 255–300 (Dumbarton Oaks Research Library and Collection, 1999).
47. Blake, M. in *Early Mesoamerican Social Transformations: Archaic and Formative Lifeways in the Soconusco Region* (ed. Lesure, R. G.) 97–118 (Univ. of California Press, 2011).
48. Hodgson, J. G., Clark, J. G. & Gallaga Murrieta, E. Ojo de Agua Monument 3: a new Olmec-style sculpture from Ojo de Agua, Chiapas, Mexico. *Mexicon* **32**, 139–144 (2010).
49. Inomata, T. in *Early Maya E Groups, Solar Calendars, and the Role of Astronomy in the Rise of Lowland Urbanism* (eds Freidel, D. A. et al.) 89–107 (Univ. Press of Florida, 2017).
50. Milbrath, S. *Star Gods of the Maya: Astronomy in Art, Folklore, and Calendars* (Univ. of Texas Press, 1999).
51. Stuart, D. *The Order of Days: the Maya World and the Truth about 2012* (Harmony Books, 2011).
52. Tedlock, B. *Time and the Highland Maya* (Univ. of New Mexico Press, 1992).
53. Aveni, A. F. *Skywatchers* (Univ. of Texas Press, 2001).
54. Aveni, A. & Hartung, H. in *World Archaeoastronomy* (ed. Aveni, A.) 441–461 (Cambridge Univ. Press, 1989).
55. Sánchez Nava, P. F. & Šprajc, I. *Orientaciones Astronómicas en la Arquitectura Maya de las Tierras Bajas* (Instituto Nacional de Antropología e Historia, 2015).
56. Aveni, A. F., Dowd, A. S. & Vining, B. Maya calendar reform? Evidence from orientations of specialized architectural assemblages. *Lat. Am. Antiquity* **14**, 159–178 (2003).
57. Milbrath, S. The role of solar observations in developing the Preclassic Maya calendar. *Lat. Am. Antiquity* **28**, 88–104 (2017).
58. Love, M. & Guernsey, J. in *Early Mesoamerican Social Transformations: Archaic and Formative Lifeways in the Soconusco Region* (ed. Lesure, R. G.) 170–188 (Univ. of California Press, 2011).
59. Rosenswig, R. M., López-Torrijos, R. & Antonelli, C. E. Lidar data and the Izapa polity: new results and methodological issues from tropical Mesoamerica. *Archaeol. Anthropol. Sci.* **7**, 487–504 (2015).
60. Sisson, E. B. *Archaeological Survey of the Chontalpa Region, Tabasco, Mexico* (Harvard Univ., 1976).
61. Borstein, J. A. *Tripping over Colossal Heads: Settlement Patterns and Population Development in the Upland Olmec Heartland.* PhD thesis, Pennsylvania State Univ. (2001).
62. Symonds, S., Cyphers, A. & Lunagómez, R. *Asentamiento Prehispánico en San Lorenzo Tenochtitlán* 1st edn, Vol. 2 (Universidad Nacional Autónoma de México, 2002).
63. von Nagy, C. L. *Of Meandering Rivers and Shifting Towns: Landscape Evolution and Community within the Grijalva Delta* (Tulane Univ., 2003).
64. Liendo Stuardo, R. *B'aakal: Arqueología de la Región de Palenque, Chiapas, México: Temporadas 1996–2006* (Archaeopress, 2011).
65. Marken, D. B. *Palenque: Recent Investigations at the Classic Maya Center* (AltaMira Press, 2007).
66. Eaton, J. D. & Ball, J. W. *Studies in the Archaeology of Coastal Yucatan and Campeche, Mexico* (Tulane Univ., 1978).
67. Scholes, F. V. & Roys, R. L. *The Maya-Chontal Indians of Acalán-Tixchel: A Contribution to the History and Ethnography of the Yucatan Peninsula* 2nd edn (Univ. of Oklahoma Press, 1968).
68. Killion, T. W. & Urcid, J. The Olmec legacy: cultural continuity and change in Mexico's southern gulf coast lowlands. *J. Field Archaeol.* **28**, 3–25 (2001).
69. Pool, C. A. et al. in *Arqueología de la Costa del Golfo: Dinámicas de la Interacción Política, Económica e Ideológica* (eds Budar, L. et al.) 269–290 (Universidad Veracruzana and Administración Portuaria Integral de Veracruz, 2017).

70. Urcid, J. & Killion, T. W. in *Classic Period Cultural Currents in Southern and Central Veracruz* (eds Arnold, P. J. III & Pool, C. A.) 259–292 (Dumbarton Oaks Research Library and Collection, 2008).
71. Stark, B. L. Formal architectural complexes in south-central Veracruz, Mexico: a capital zone? *J. Field Archaeol.* **26**, 197–225 (1999).
72. Stark, B. L. in *Alternative Pathways to Complexity: A Collection of Essays on Architecture, Economics, Power, and Cross-Cultural Analysis* (eds Fargher, L. F. & Heredia Espinoza, V. Y.) 105–130 (Univ. Press of Florida, 2016).
73. Daneels, A. in *Olmec to Aztec: Settlement Patterns in the Ancient Gulf Lowlands* (eds Stark, B. L. & Arnold, P. J. III) 206–252 (Univ. of Arizona Press, 1997).
74. Daneels, A. *El Patrón de Asentamiento del Periodo Clásico en la Cuenca Baja del Río Cotaxtla, Centro de Veracruz* (Universidad Nacional Autónoma de México, 2002).
75. Daneels, A. in *Classic Period Cultural Currents in Southern and Central Veracruz* (eds Arnold, P. J. III & Pool, C. A.) 197–224 (Dumbarton Oaks Research Library and Collections, 2008).
76. Stark, B. L. & Eschbach, K. L. Collapse and diverse responses in the Gulf lowlands, Mexico. *J. Anthropol. Archaeol.* **50**, 98–112 (2018).
77. Siemens, A. H. & Paleston, D. E. Ridged fields and associated features in southern Campeche: new perspectives on the lowland Maya. *Am. Antiquity* **37**, 228–239 (1972).
78. Dunning, N. P. et al. The ancient Maya wetland fields of Acalán. *Mexicon* **42**, 91–105 (2020).
79. Beach, T. et al. Ancient Maya wetland fields revealed under tropical forest canopy from laser scanning and multiproxy evidence. *Proc. Natl Acad. Sci. USA* **116**, 21469–21477 (2019).
80. Matheny, R. T. *The Ceramics of Aguacatal, Campeche, Mexico* (Brigham Young Univ., 1970).
81. Perales Vela, R. & Mugarte, J. in *Seis Ensayos Sobre Antiguos Patrones de Asentamiento en el Area Maya* (ed. Vargas Pacheco, E.) 27–52 (Universidad Nacional Autónoma de México, 1995).
82. Suárez, V. & Rocha, F. in *Los Investigadores de la Cultura Maya* No. 9, Vol. 1 (eds Benavides Castillo, A. & Matheny, R. T.) 66–79 (Universidad Autónoma de Campeche, 2001).
83. Aoyama, K. Classic Maya warfare and weapons: spear, dart, and arrow points of Aguateca and Copan. *Anc. Mesoam.* **16**, 291–304 (2005).
84. Brown, M. K. & Stanton, T. W. *Ancient Mesoamerican Warfare* (AltaMira, 2003).
85. Demarest, A. A., Quintanilla, C. & Suasnavar, J. S. in *Ritual, Violence, and the Fall of the Classic Maya Kings* (eds Iannone, G. et al.) 159–186 (Univ. Press of Florida, 2016).
86. Demarest, A. A. The Vanderbilt Petexbatun Regional Archaeological Project 1989–1994: overview, history, and major results of a multidisciplinary study of the Classic Maya collapse. *Anc. Mesoam.* **8**, 209–228 (1997).
87. Inomata, T. in *Embattled Bodies, Embattled Places: War in Pre-Columbian America* (eds Scherer, A. K. & Verano, J.) 25–56 (Dumbarton Oaks Research Library and Collection, 2014).
88. Inomata, T. *Warfare and the Fall of a Fortified Center: Archaeological Investigations at Aguateca* (Vanderbilt Univ. Press, 2007).
89. Inomata, T. in *The Archaeology of Settlement Abandonment in Middle America* (eds Inomata, T. & Webb, R. W.) 43–60 (Univ. of Utah Press, 2003).
90. Scherer, A. K. & Golden, C. in *Embattled Bodies, Embattled Places: War in Pre-Columbian America* (eds Scherer, A. K. & Veran, J.) 57–92 (Dumbarton Oaks Research Library and Collection, 2014).
91. Webster, D. *The Fall of the Ancient Maya* (Thames and Hudson, 2002).
92. Webster, D. L. in *Lowland Maya Civilization in the Eighth Century AD* (eds Sabloff, J. A. & Henderson, J. S.) 415–444 (Dumbarton Oaks Research Library and Collection, 1993).
93. Wahl, D., Anderson, L., Estrada-Belli, F. & Tokovinine, A. Palaeoenvironmental, epigraphic and archaeological evidence of total warfare among the Classic Maya. *Nat. Hum. Behav.* **3**, 1049–1054 (2019).
94. Pugh, T. W. From the streets: public and private space in an early Maya city. *J. Archaeol. Method Theory* **26**, 967–997 (2019).
95. Fernandez-Diaz, J. C., Carter, W. E., Shrestha, R. L. & Glennie, C. L. Now you see it … now you don't: understanding airborne mapping LiDAR collection and data product generation for archaeological research in Mesoamerica. *Remote Sens.* **6**, 9951–10001 (2014).
96. Fernandez-Diaz, J. C. et al. Capability assessment and performance metrics for the Titan multispectral mapping lidar. *Remote Sens.* **8**, 936 (2016).
97. Fisher, C. T. et al. Identifying ancient settlement patterns through LiDAR in the Mosquitia region of Honduras. *PLoS ONE* **11**, e0159890 (2016).
98. Fisher, C. T., Cohen, A. S., Fernández-Diaz, J. C. & Leisz, S. J. The application of airborne mapping LiDAR for the documentation of ancient cities and regions in tropical regions. *Quat. Int.* **448**, 129–138 (2017).
99. Stanton, T. W. et al. 'Structure' density, area, and volume as complementary tools to understand Maya Settlement: an analysis of lidar data along the great road between Coba and Yaxuna. *J. Archaeol. Sci. Rep.* **29**, 102178 (2020).
100. Brewer, J. L. et al. Employing airborne lidar and archaeological testing to determine the role of small depressions in water management at the ancient Maya site of Yaxnohcah, Campeche, Mexico. *J. Archaeol. Sci. Rep.* **13**, 291–302 (2017).
101. Chase, A. F. et al. The use of LiDAR in understanding the ancient Maya landscape. *Adv. Archaeol. Pract.* **2**, 208–221 (2014).
102. Hare, T., Masson, M. & Russell, B. High-density LiDAR mapping of the ancient city of Mayapán. *Remote Sens.* **6**, 9064–9085 (2014).
103. Inomata, T. et al. Archaeological application of airborne LiDAR with object-based vegetation classification and visualization techniques at the lowland Maya site of Ceibal, Guatemala. *Remote Sens.* **9**, 563 (2017).
104. Murtha, T., Golden, C., Cyphers, A., Klippel, A. & Flohr, T. Beyond inventory and mapping: LIDAR, landscape and digital landscape architecture. *J. Digit. Landsc. Archit.* **3**, 249-259 (2018).
105. Cook, B. D. et al. NASA Goddard's LiDAR, hyperspectral and thermal (G-LiHT) airborne imager. *Remote Sens.* **5**, 4045–4066 (2013).
106. Golden, C. et al. Reanalyzing environmental lidar data for archaeology: Mesoamerican applications and implications. *J. Archaeol. Sci. Rep.* **9**, 293–308 (2016).
107. Chiba, T., Kaneta, S.-i & Suzuki, Y. Red relief image map: new visualization method for three dimensional data. *Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci.* **37**, 1071–1076 (2008).
108. Chiba, T. & Suzuki, Y. Visualization of airborne laser mapping data: production and development of red relief image map (in Japanese). *Adv. Surv. Technol.* **96**, 32–42 (2008).
109. Casana, J. Regional-scale archaeological remote sensing in the age of big data: automated site discovery vs. brute force methods. *Adv. Archaeol. Pract.* **2**, 222–233 (2014).
110. Berlin, H. in *Current Report* Vol. 7 (ed Pollock, H. E. D.) 101–130 (Carnegie Institution, 1953).
111. Blom, F. F. & La Farge, O. *Tribes and Temples; A Record of the Expedition to Middle America* (The Tulane Univ. of Louisiana, 1926).
112. Ochoa, L. & Hernández, M. I. Los olmecas y el valle del Usumacinta. *An. de. Antropol.ía* **14**, 75–90 (1977).
113. Ochoa, L. in *Antropología e Historia de los Mixe-Zoques y Mayas: Homenaje a Frans Blom* (eds Ochoa, L. & Lee, T. A.) 147–174 (UNAM, 1983).
114. Tejedo, F., Gaxiola, I. M., Camacho, J. L. & Ramírez C, E. *Zonas Arqueológicas, Tabasco* (Instituto Nacional de Antropología e Historia, 1988).
115. West, R. C., Psuty, N. P. & Thom, B. G. *The Tabasco Lowlands of Southeastern Mexico* (LSU Press, 1969).
116. Witschey, W. R. T. & Brown, C. T. in *The Ancient Maya of Mexico: Reinterpreting the Past of the Northern Maya* (ed Braswell, G. E.) 184–202 (Equinox Publishing, 2014).
117. Stoner, W. D. Modeling and testing polity boundaries in the Classic Tuxtla mountains, southern Veracruz, Mexico. *J. Anthropol. Archaeol.* **31**, 381–402 (2012).
118. Santley, R. S. *The Prehistory of the Tuxtlas* (Univ. of New Mexico Press, 2007).
119. Ensor, B. E. & Ayora, G. T. The site of El Bellote, Tabasco, Mexico and preliminary observations on Late Classic period Chontal regional integration. *Mexicon* **33**, 116–126 (2011).
120. Ensor, B. E. *Oysters in the Land of Cacao: Archaeology, Material Culture, and Societies at Islas de Los Cerros and the Western Chontalpa, Tabasco, Mexico* (Univ. of Arizona Press, 2020).
121. Kruger, R. P. *An Archaeological Survey in the Region of the Olmec, Veracruz, Mexico.* PhD thesis, Univ. of Pittsburgh (1996).
122. Rust, W. F. *A Settlement Survey of La Venta, Tabasco, Mexico*. PhD thesis, Univ. of Pennsylvania (2008).
123. Inomata, T. *Middle Usumacinta Archaeological Project Tabasco Veracruz Site Database*, https://repository.arizona.edu/handle/10150/659895 (Univ. of Arizona Campus Repository, 2021).
124. Hernández Jiménez, M. D. L. *Supervisión Arqueológica Almagres 2D* Informe Técnico Final (Centro INAH Veracruz, 2007).
125. Hernández Jiménez, M. D. L. *Supervisión Arqueológica Almagres 2D, Ampliación Bloque Chalca* Informe Técnico Final (Centro INAH Veracruz, 2008).
126. Hernández Jiménez, M. D. L. & Moreno Díaz, M. *Programa Emergente de Inspección Aqueológica en el Estudio Sísmico Tepetate NW-El Plan-Los Soldados 3D* Informe Técnico Parcial (Centro INAH Veracruz, 2010).
127. Hernández Jiménez, M. D. L. & Moreno Díaz, M. *Supervisión Arqueológica Tepetate-El Plan-Los Soldados 3D* Informe Técnico Parcial (Centro INAH Veracruz, 2011).
128. Hernández Jiménez, M. D. L. & Moreno Díaz, M. *Supervisión Arqueológica Chalchijapa-Sauzal 2D* Informe Técnico Final (Centro INAH Veracruz, 2011).
129. Hernández Jiménez, M. D. L. & Moreno Díaz, M. *Supervisión Arqueológica Tepetate NW-El Plan-Los Soldados 3D* Informe Técnico Final (Centro INAH Veracruz, 2012).
130. Hernández Jiménez, M. D. L. & Moreno Díaz, M. *Informe Técnico Salsomera 2D* (Centro INAH Veracruz, 2014).

131. Hernández Jiménez, M. D. L. & Moreno Díaz, M. *Supervisión Arqueológica Tepetate NW-El Plan-Los Soldados, Ampliación Cerro Nanchital 3D* Informe Técnico Final (Centro INAH Veracruz, 2014).
132. Hernández Jiménez, M. D. L. Asentamientos arqueológicos del municipio de las Choapas, Veracruz. *LiminaR* **10**, 122–137 (2012).
133. Hernández Jiménez, L. Reconocimiento extensivo en la región sur de Veracruz. *Ollin* **10**, 23–30 (2012).
134. Stark, B. L. *Classic Period Mixtequilla, Veracruz, Mexico: Diachronic Inferences from Residential Investigations* (Institute for Mesoamerican Studies University at Albany; distributed by Univ. of Texas Press, 2001).
135. Stark, B. L. *The Archaeology of Political Organization: Urbanism in Classic Period Veracruz, Mexico* (Cotsen Institute Press, 2020).
136. Loughlin, M. L. *El Mesón Regional Survey: Settlement Patterns and Political Economy in the Eastern Papaloapan Basin, Veracruz, Mexico.* PhD thesis, Univ of Kentucky (2012).
137. Kruszczynski, M. A. R. *Prehistoric Basalt Exploitation and Core-Periphery Relations Observed from the Cerro El Vigía Hinterland of Tres Zapotes, Veracruz, Mexico.* PhD thesis, Univ. of Pittsburgh (2001).
138. Santley, R. S. The economy of ancient Matacapan. *Anc. Mesoam.* **5**, 243–266 (1994).
139. Wendt, C. J., Bernard, H. N. & Delsescaux, J. A Middle Formative artifact excavated at Arroyo Pesquero, Veracruz. *Anc. Mesoam.* **25**, 309–316 (2014).
140. Romero Rivera, J. L. in *Seis Ensayos Sobre Antiguos Patrones de Asentamiento en el Area Maya* (ed. Vargas Pacheco, E.) 15–27 (UNAM, 1995).
141. Teranishi Castillo, K. in *XXIII Simposio de Investigaciones Arqueológicas en Guatemala, 2009* (eds Arroyo, B. et al.) 210–223 (Museo Nacional de Arqueología y Etnología, 2010).
142. Ek, J. D. *Resilience in the Midst of Collapse: A Regional Case Study of Socio-Ecological Dynamics in the Río Champotón Drainage, Campeche, Mexico.* PhD thesis, State Univ. of New York at Albany (2015).
143. González Lauck, R. B. in *The Place of Stone Monuments: Context, Use, and Meaning in Mesoamerica's Preclassic Tradition* (eds Guernsey, J. et al.) 177–205 (Dumbarton Oaks Research Library and Collection, 2010).

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Author contributions
T.I. conceptualized the research. J.F.-D. coordinated the NCALM lidar data acquisition and processing, and reprocessed the INEGI and G-LiHT lidar. T.I., M.G.M, F.P. and M.G.H. analysed lidar data for the identification of archaeological features. T.I. and T.B. identified wetland fields in lidar data. J.D.D., A.G.L. and L.G.C. provided information on the INEGI lidar. T.I., D.T., M.G.M, F.P., M.G.H. and A.F. conducted field investigations in the Middle Usumacinta region and M.L.H.J. and M.M.D. carried out surveys in southern Veracruz. A.S. analysed faunal remains. G.H. conducted radiocarbon analysis and T.I. and G.H. evaluated radiocarbon dates. T.I. conducted the Bayesian analysis of radiocarbon dates. T.I. wrote the manuscript with input from others.

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The authors declare no competing interests.

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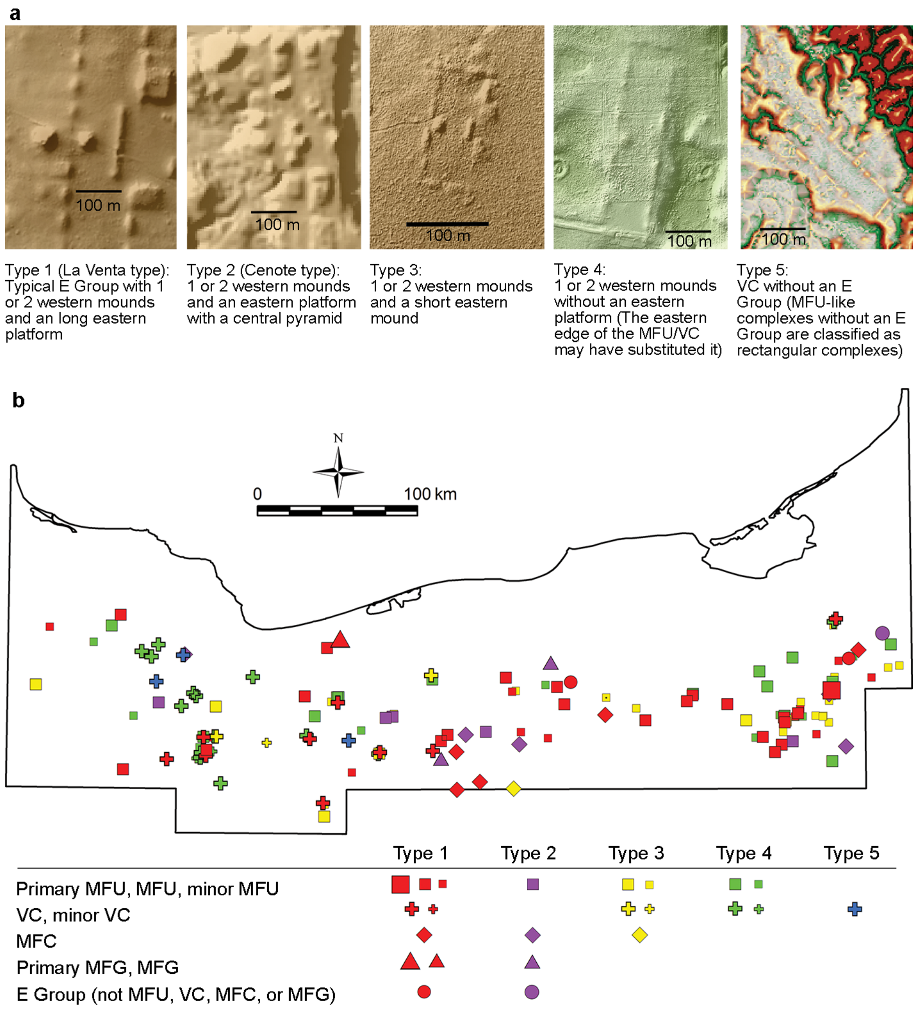
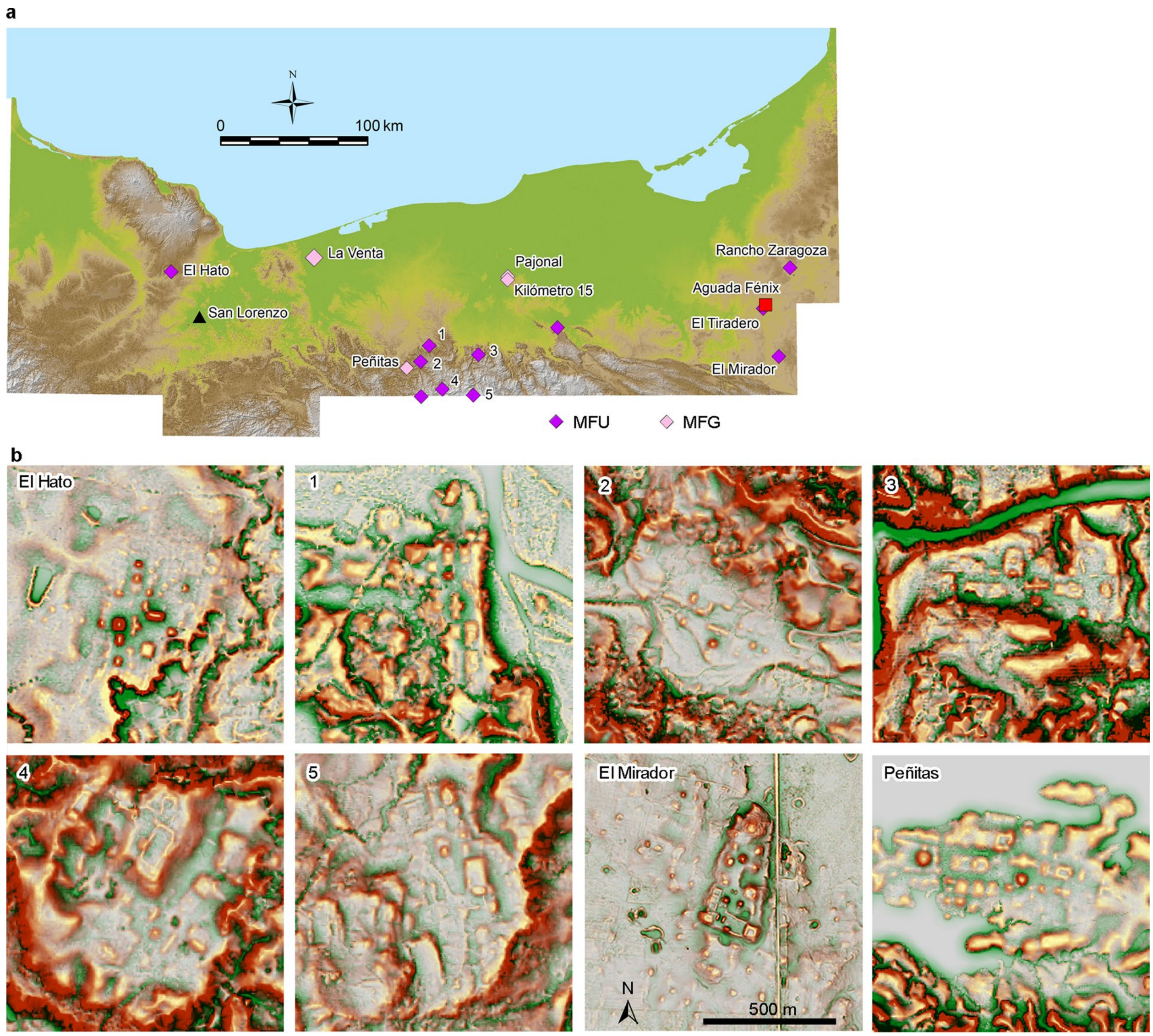
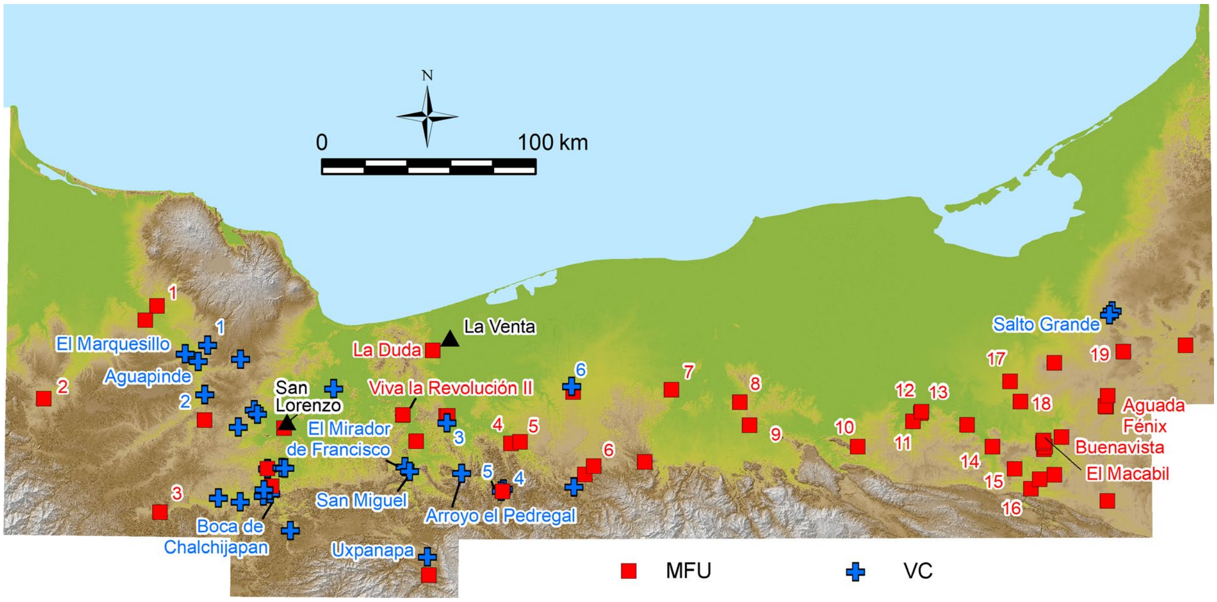


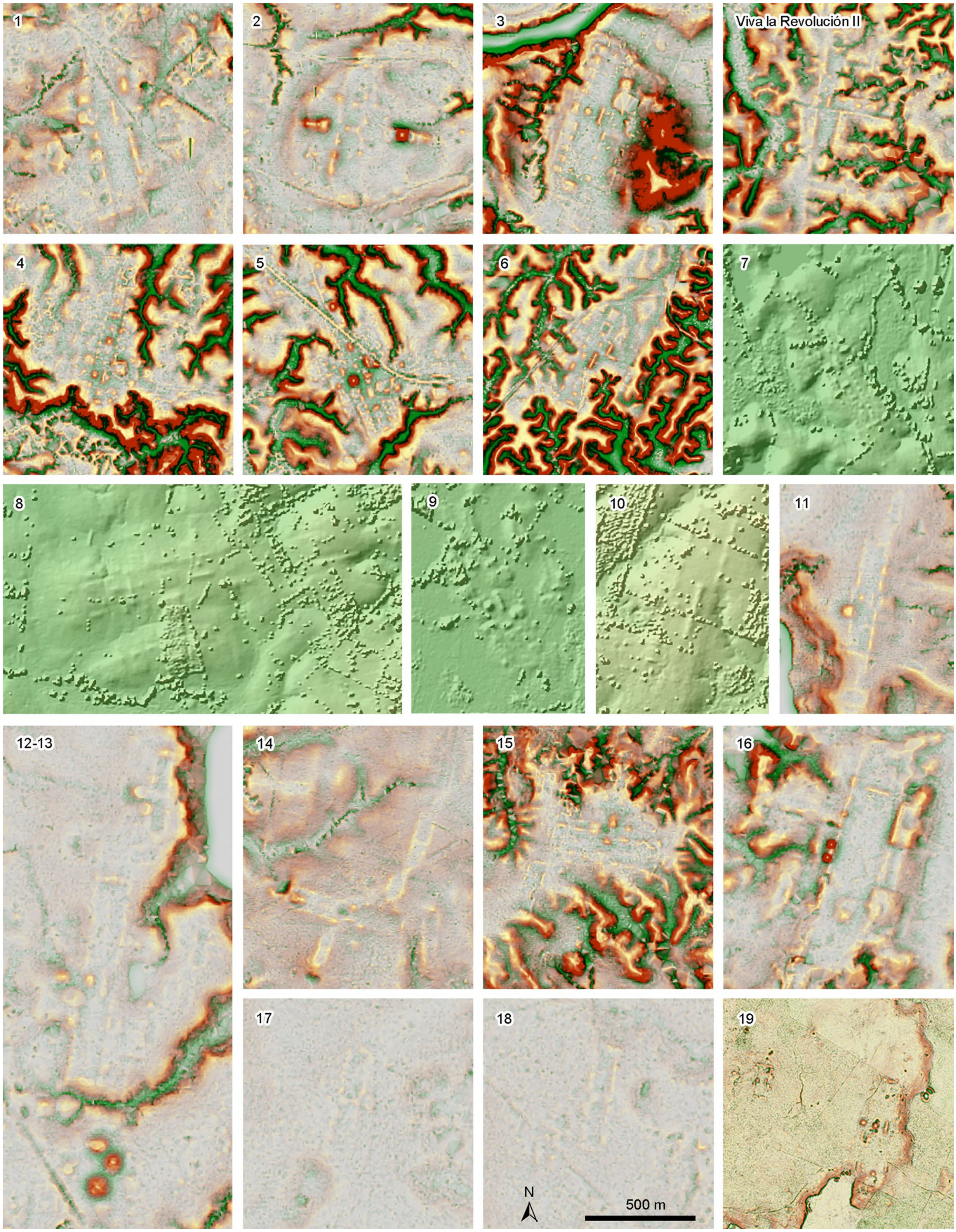
Extended Data Fig. 1 | E Groups. a, Types of E Groups. **b**, Locations of E Groups by type. Only complexes identified in the INEGI lidar are plotted.



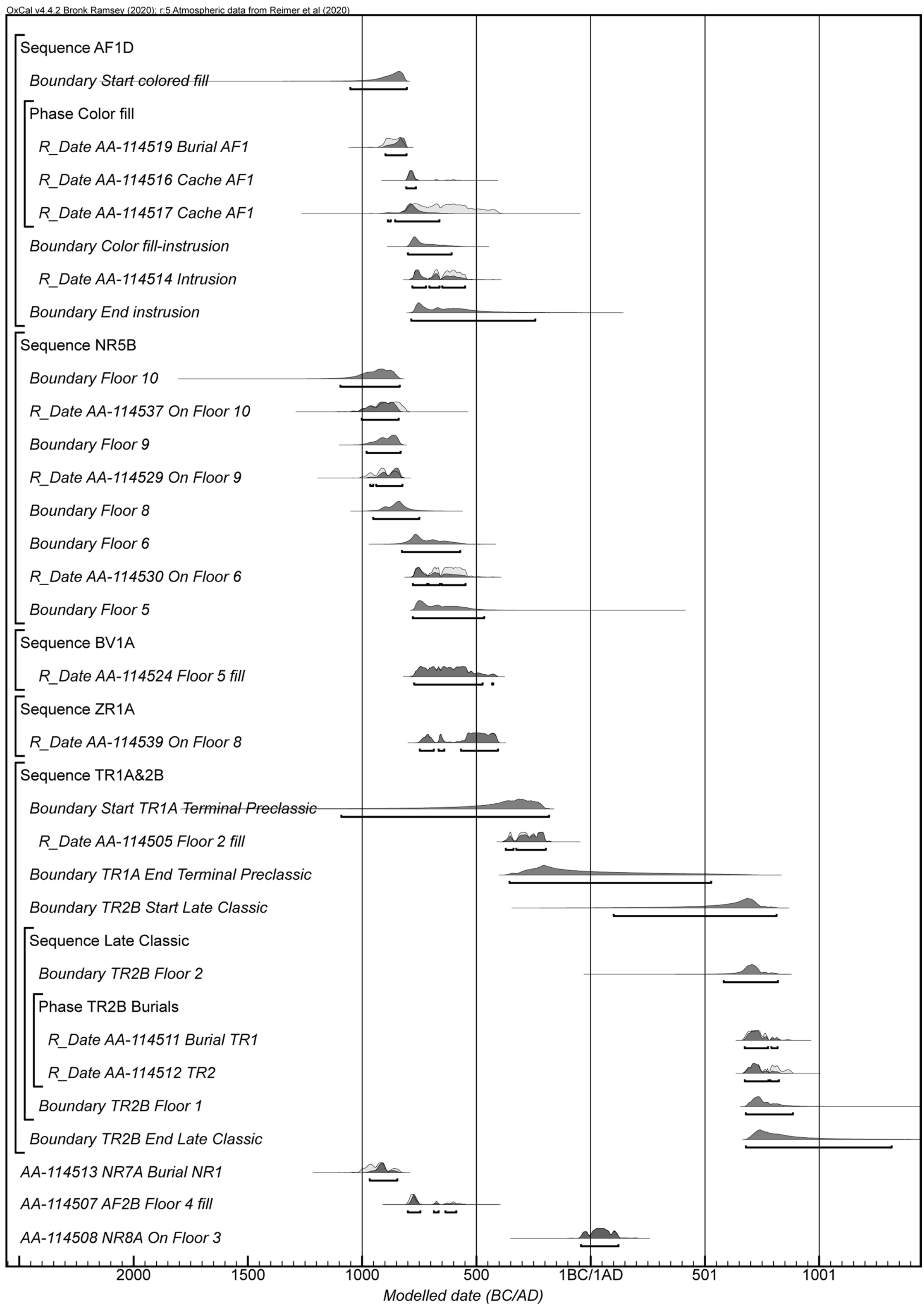
Extended Data Fig. 2 | MFCs and MFGs. a, Locations of MFCs and MFGs. **b**, MFCs and an MFG (Peñites) shown in RRIM (DEM). All images are on the same scale.



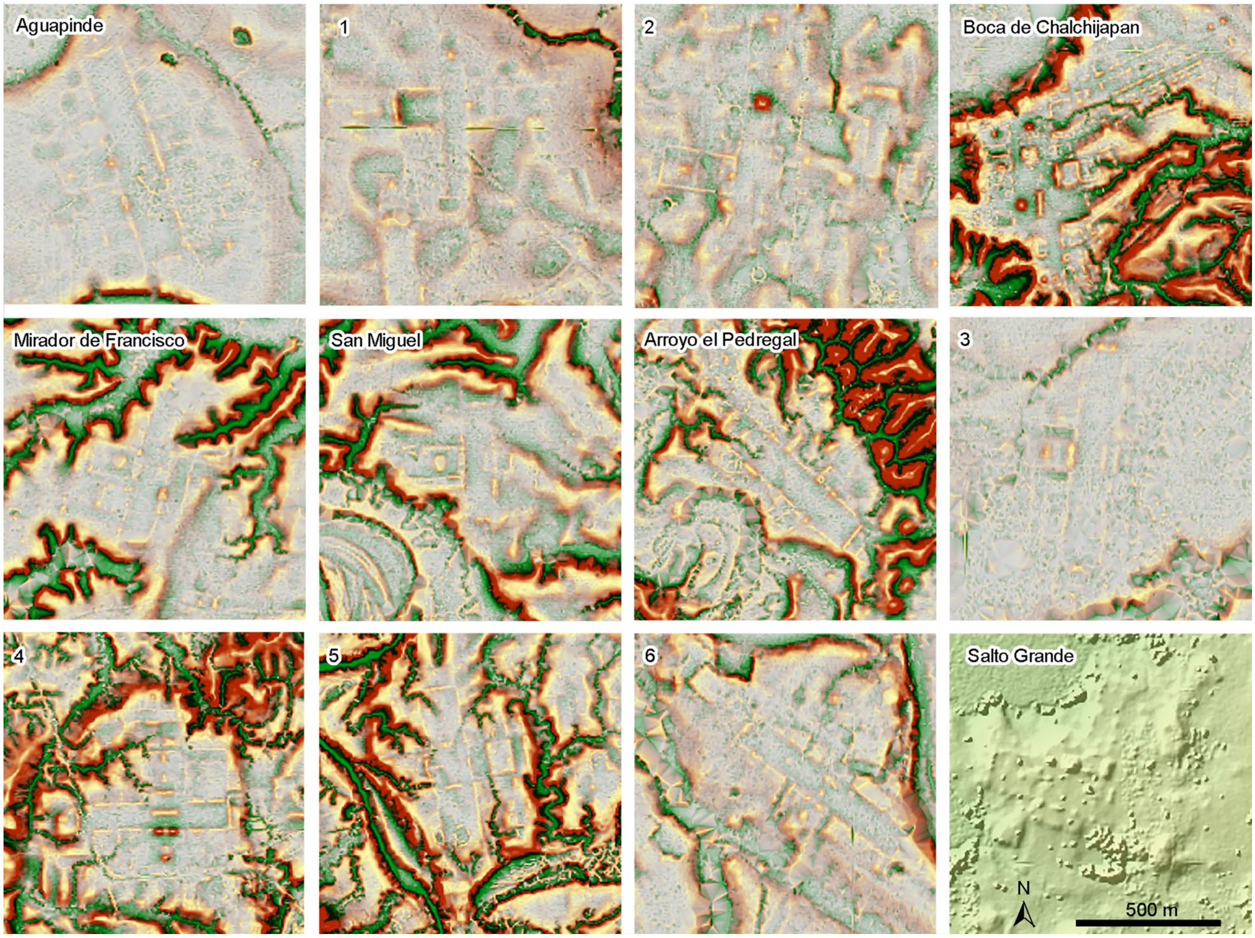
Extended Data Fig. 3 | Locations of MFUs and VCs. The numbers indicate the locations of the sites shown in Extended Data Figs. 4 and 5.



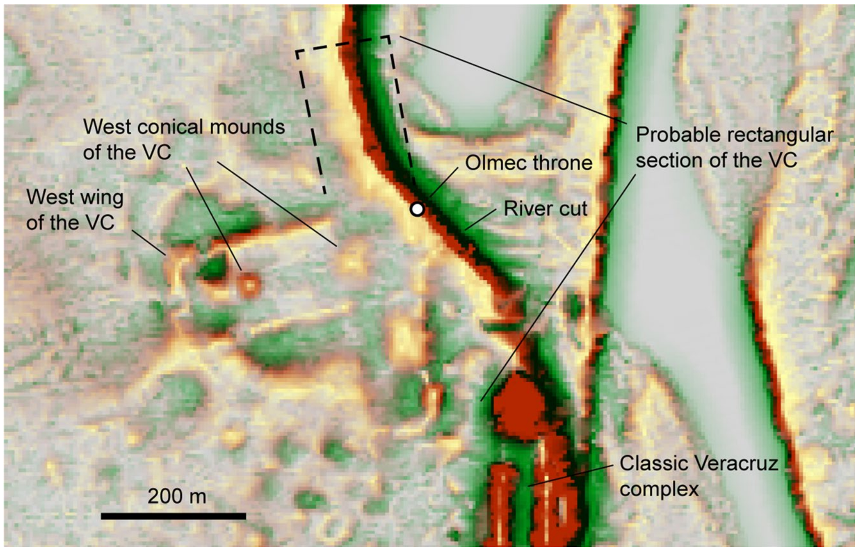
Extended Data Fig. 4 | Examples of MFUs. See Extended Data Fig. 3 for their locations. The images are shown in RRIM (DEM) and hillshade (DSM). All images are on the same scale.



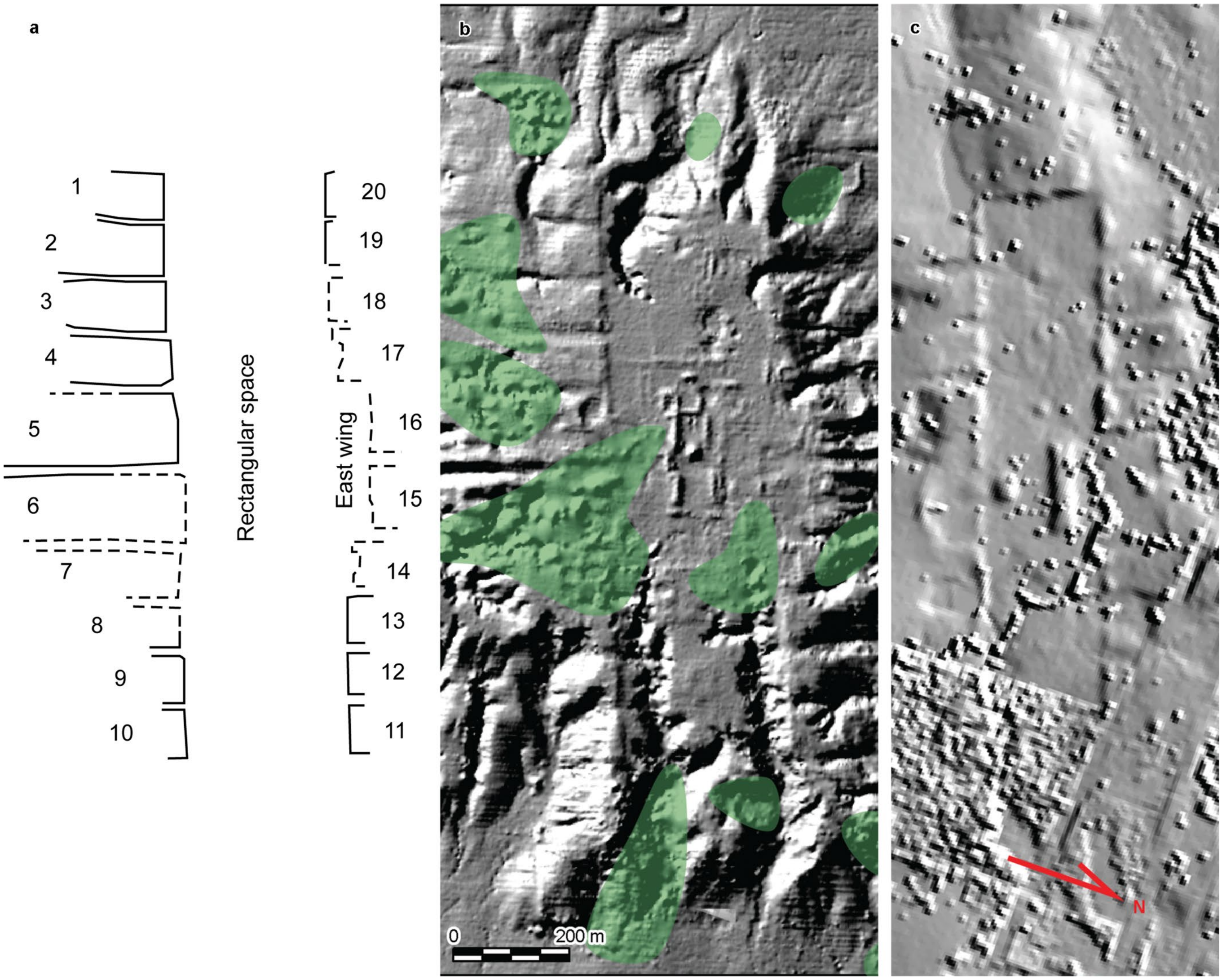
Extended Data Fig. 5 | Oxcal output of the manual rejection model for the 2020 samples. Outliers are excluded from the output. The grey areas indicate the probability distributions of unmodelled dates, whereas the black areas show the probability distributions of modelled dates. The bars under the probability distributions indicate the 95.4 % ranges.



Extended Data Fig. 6 | Examples of VCs. See Extended Data Fig. 3 for their locations. The images are shown in RRIM (DEM) and hillshade (DSM). All images are on the same scale.



Extended Data Fig. 7 | El Marquesillo possibly exhibiting the VC pattern. It is shown in the RRIM of the INEGI DEM.



Extended Data Fig. 8 | San Lorenzo and La Duda. The images are on the same scale, but the image of La Duda is rotated. See Extended Data Fig. 3 for their locations. **a**, Edge platforms and the central rectangular space of San Lorenzo. **b**, San Lorenzo. The 2 m-resolution DEM reprocessed from the INEGI lidar data is shown as a hillshade image. The areas of dense vegetation, which laser pulses did not penetrate well, are indicated in half-transparent green. Other areas have pastures or sparse vegetation. In clear areas, details of the surface topography are visible. To produce this DEM, we manually cleaned some vegetation returns only in the areas covered by dense vegetation. The DEM shows the rectangular shapes of edge platforms, which define the straight edges of the possible rectangular plaza in the middle. The buildings in the centre of the probable plaza represent a Classic Veracruz complex added during the Villa Alta phase. **c**, The MFU complex of La Duda. The 5 m-resolution INEGI DSM is shown as a hillshade image. Its northeastern part is damaged by modern road construction, and its eastern end is covered by dense vegetation. Its edge platforms (possibly 20 of them) separated by narrow alleys and the rectangular plaza with a wing on the viewer's right are visible. Its configuration is similar to that of San Lorenzo. The main difference is the presence of an E Group.

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Software and code

Policy information about availability of computer code

Data collection	Lidar data acquisition and processing were done with Optech LMS 4.4.0, Terrasolid TerraScan 20.04 and Golden Software Surfer 16.
Data analysis	Lidar-derived DEMs were analyzed with ESRI ArcGIS 10.7.1 and QGIS 3.10.2. The Bayesian analysis of radiocarbon dates was done with Oxcal 4.4.2. The Oxcal codes for this analysis are included as Supplementary Information. The analysis of sunrise directions was done with Stellarium 0.19.3.

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All studies must disclose on these points even when the disclosure is negative.

Study description	This is an archaeological study of past society. The primary data derive from lidar surveys. Information on dates and material cultures were obtained through excavations, pedestrian surveys and radiocarbon dating. The study involves quantitative data on site distribution, site sizes and radiocarbon dates. It also includes the qualitative study of site plans, spatial use and social processes.
Research sample	The primary data on site distribution and site forms were obtained from the publicly available lidar data of the INEGI (www.inegi.org.mx). The lidar covers the entire study area of 84,516 km2 in southern Mexico, and thus the data are representative. We also examined high-resolution lidar data for areas of 1,015 km2 obtained by the NCALM, 99 km2 obtained by NASA G-LiHT (publicly available) and 10 km2 obtained by CCGS. The coverage by the high-resolution lidar is not representative, but it provides adequate data for the verification of the INEGI lidar. Locations for excavations were chosen purposefully to obtain necessary data efficiently.
Sampling strategy	The INEGI lidar covers the entire study area, and we recorded all archaeological sites that are detectable in this lidar dataset. The areas for the NCALM lidar were chosen purposefully to examine important sites. No sample size calculation was performed.
Data collection	The INEGI and G-LiHT lidar data were obtained before our research and were made publicly available. We analyzed these publicly-available data. The NCALM data were collected with Optech Titan lidar. Excavation data were recorded on paper forms in the field and then input in computer files. Photographs of excavations were taken with Nikon D750 and D7000 digital cameras. In addition to the authors of this paper, other archaeologists, archaeology students, and local community members participated in excavations.
Timing	NCALM lidar data were collected in May 2017 and June 2019. Lidar data were analyzed December 2017-June 2020. Archaeological fieldwork was conducted July-August 2017, February-April 2018, February-April 2019 and February-March 2020.
Data exclusions	No lidar and excavation data were excluded. In the Bayesian analysis of radiocarbon dates, probable outliers were excluded from the models. This is a standard procedure for this analysis. By comparing sequences of stratigraphically-related radiocarbon dates, we identified those affected by stratigraphic mixing or the use of old wood. We also examined the statistical indicators of outliers (agreement index calculated by Oxcal). In addition, we made an outlier model of Oxcal, which statistically identified probable outliers.
Non-participation	The study did not involve human participants.
Randomization	The study did not involve human participants. Lidar and excavation data were not randomized.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study	
☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology and archaeology
☒	☐	Animals and other organisms
☒	☐	Human research participants
☒	☐	Clinical data
☒	☐	Dual use research of concern

Methods

n/a	Involved in the study	
☒	☐	ChIP-seq
☒	☐	Flow cytometry
☒	☐	MRI-based neuroimaging