Journal of Archaeological Science: Reports 55 (2024) 104528



Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep





Teotihuacan ancient culture affected by megathrust earthquakes during the early Epiclassic Period (Mexico)

Raúl Pérez-López [a,*], Natalia Moragas-Segura [b], Javier Elez [c], Pablo G. Silva [c], Jorge L. Giner-Robles [d], Miguel A. Rodríguez-Pascua [a], Adrià Ramos [a], María A. Perucha [a], Elvira Roquero [e], Víctor H. Garduño-Monroy [f]

[a] Instituto Geológico y Minero de España, IGME (CSIC), C/ Rios Rosas 23, 28003 Madrid, Spain
[b] Dpto. de Historia y Arqueología, Universidad de Barcelona, 08001 Barcelona, Spain
[c] Dpto. de Geología, Universidad de Salamanca, Escuela Politécnica Superior, 05003 Avila, Spain
[d] Dpto. de Geología y Geoquímica, Universidad Autónoma de Madrid, Cantoblanco, 28049 Madrid, Spain
[e] Dpto. de Edafología, E.T.S.I. Agrónomo, Universidad Politécnica de Madrid, 28040 Madrid, Spain
[f] Universidad Michoacana San Nicolas de Hidalgo, Morelia, Mexico

ARTICLE INFO

Keywords:
Teotihuacan
Archaeoseismology
Classic-Epiclassic
Earthquake
Mexico

ABSTRACT

Teotihuacan was one of the thriving cultures in the Mesoamerica pre-Hispanic times, located in the Central Valley of Mexico. The city-state was a dominant centre point during the Classic period and its influence affected other contemporaneous cultures. Around the year 550 CE, a continuous decrease in urban population and selective building destruction was noted, accompanied by widespread fire. The layout of the city is identified by an avenue that articulates the political-administrative and religious centres, with such significant and impressive buildings as the Pyramid of the Sun, the Pyramid of the Moon and the Temple of Feathered Serpent. A systematic analysis of building damage in the pyramids reveals several Earthquake Archaeological Effects, (EAEs) potentially related to seismic loading. A damage pattern compatible with a strong ground shaking was also identified in the west staircase of the Old Temple of the Feathered Serpent, in the first rows of the west staircase of the Adosada platform (New Temple), and in the Pyramid of the Sun. In total, five ancient earthquakes have been determined from the damage, dated from the Tzacualli cultural period (1–100 CE), to the Xolalpan – Metepec period (450–550 CE). Unfortunately, this methodology does not determine the earthquake source. Therefore, we consider the possibility that repetitive megathrust earthquakes (Mw > 8.5) from the Middle American Trench (Pacific coast) could be responsible for the spatial pattern of the building damage. This proposal does not conflict with other existing theories for the Teotihuacan abrupt collapse, considering that the sudden overlapping of natural disasters like earthquakes could increase internal warfare (uprising), and civil unrest.

1. Introduction

The Mesoamerican cultures have experienced destructive earthquakes since the dawn of the American civilizations (Kovacs, 2004; Garduño-Monroy, 2016; Rodríguez-Pascua et al., 2020, 2021a). The Teotihuacan culture flourished in the Central Valley of Mexico between the years 150 BCE to 650 CE (Fig. 1), a civilization that raised a highly mature society, and built splendorous pyramids and temples (Sugiyama and Cabrera-Castro, 2007; Sugiyama et al., 2013; Moragas-Segura, 2013; Manzanilla, 2015). The rise and rapid growth of Teotihuacan has been related to the Popocatepetl volcanic eruption (50–100 CE, Manzanilla, 2015), and it was probably reinforced by the Xitle volcanic eruption affecting Cuicuilco city (~300 CE, Siebe, 2000). Both volcanic eruptions left Teotihuacan as a strategic point of union within the Central Valley of Mexico (Carballo, 2018).

Kovacs (2004) points out the possibility of an earthquake as the cause for the collapse of the different buildings observed by archaeologists at Teotihuacan. Pérez-López et al., (2010), (2019), and Pérez-López (2012), described the Earthquakes Archaeological Effects (EAEs) affecting the Pyramid of the Sun, and the Temple of the Feathered Serpent (also known as Temple of the Quetzalcoatl), according to the EAE classification defined in Rodríguez-Pascua et al. (2011). These EAEs

* Corresponding author.
E-mail address: r.perez@igme.es (R. Pérez-López).

https://doi.org/10.1016/j.jasrep.2024.104528
Received 13 September 2021; Received in revised form 8 April 2024; Accepted 9 April 2024
Available online 11 April 2024
2352-409X/© 2024 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC license (http://creativecommons.org/licenses/by-nc/4.0/).

identified in Teotihuacan are dipping broken corners (chipped corners), displacement and rotation of masonry blocks, collapse of walls, and destruction of the upper parts of buildings. Additionally, a new type of EAE, the floating-dipping-broken corner affecting hanging-blocks of the temples' facade, supports the seismic origin instead of man-made breaking or natural weathering of basalts under dry climate conditions (Viles et al., 2018).

In this work, we have carried out a systematic archaeoseismological analysis from EAEs observed and collected at the pyramids (the Temple of the Feathered Serpent, the Pyramid of the Sun, the Pyramid of the Moon), and from the archaeological information compiled in several works (Millon, 1988; Sugiyama, 1989; Rattray, 1991; Sugiyama and Cabrera-Castro, 2007; Sugiyama et al., 2013; Manzanilla, 2015). Although the methodology cannot determine the source of the potential destructive earthquake (Rodríguez-Pascua et al., 2011), we have estimated the possibility of a seismic source from a megathrust earthquake located at far-field in the Middle American Trench, a major subduction zone in the Pacific Ocean. The Pacific west coast of Mexico is a well-known source of megathrust earthquakes (magnitude larger than M 8.5). Nevertheless, an intraplate earthquake could not be discarded in the Mexico basin. In total, five destructive ancient earthquakes have been estimated to hit Teotihuacan between the Tzacualli – Miccaotli (100–150 CE), and Metepec (600 ± 50 CE) stages, by matching EAEs and archaeological dates.

The novelty of this work is the likelihood of those earthquakes being the cause for the evolution of the architectural style of the *teotihuacanos*, in enlarging the main religious and political buildings, the Sun and the Moon pyramids, and rebuilding the Temple of the Feathered Serpent.

2. Methods

Large earthquakes are often assumed to be responsible for the destruction of buildings and cultural changes in archaeology (i.e. Kovacs, 2004). However, the assignment of destructive earthquakes affecting ancient civilizations has to be carried out with a different approach to avoid the misinterpretation of destruction layers due to other causes, like warfare, city abandonment, or internal social revolts. We have applied two different approaches to fit the occurrence of large earthquakes which could be one of the reasons contributing to the declination and abandonment of Teotihuacan, (1) Archaeoseismology, the study of destructive earthquakes affecting ancient cultures by the geological effects of earthquakes, building damage, and archaeological studies (Nikonov, 1988; Guidoboni, 1989; Stiros and Jones, 1996; Hancock and Stewart, 2001; Silva et al., 2005; Marco, 2008; Sintubin et al., 2010; Rodríguez-Pascua et al., 2011), and (2) the study of the potential seismic sources, the orientation of the seismogenic fault, and the capability to trigger large earthquakes. Moreover, the site effects and lacustrine infilling of the base ground of the Teotihuacan, associated with the Lake Texcoco, probably amplified the seismic signal increasing building damage (Anderson et al., 1986).

Giner-Robles et al. (2009) and Silva et al. (2009) mapped earthquake damage affecting buildings and pavements in the ancient Roman city of Baelo Claudia, southern Spain. These authors measured the spatial orientation of the damage, pavement folding, and fractures in masonry, tilted and folded walls, and the drop of arch keystones. Afterwards, they mapped in the layout of the city the trajectories of the ground vibration. Both authors plotted rose diagrams and cyclograph stereograms of the EAEs directivity to determine the Seismic Ray direction and the spatial pattern of the destruction. Thus, they discriminate the seismic origin of the city destruction in comparison with other potential origins, such as war or abandonment. In warfare cases, no anisotropy or spatial damage arrangement will be observed in a city layout.

Rodríguez-Pascua et al. (2011) introduced the Earthquake Archaeological Effects (EAEs) to describe patterns of destruction generated by earthquakes affecting urban cities, regardless of the culture or type of building construction. In this work, we have applied the methodology

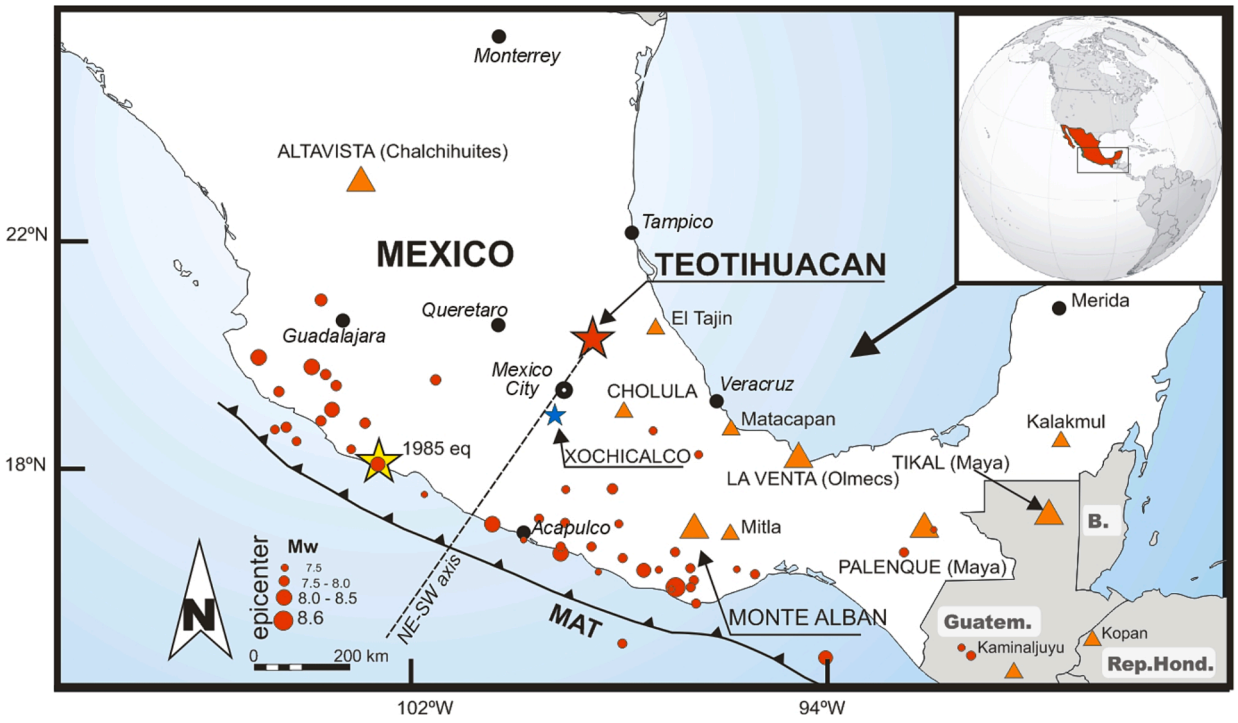

Fig. 1. Geographical location of Teotihuacan city-state (red star) and some contemporaneous cities (orange triangles) during the Classic and Epiclassic. The blue star shows the city of Xochicalco. MAT is the Middle American Trench. Modern cities are also indicated (solid black dots). Epicentres of historical and instrumental earthquakes with magnitude M ≥ 7.5 are indicated (red dots) from Sawires et al. (2019) database (1787–2018). B. Belize, Guatem. Guatemala, Hond. Republic of Honduras. The yellow star indicates the epicentre of the Michoacan earthquake of 1985 (Anderson et al., 1986). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

proposed by Rodríguez-Pascua et al. (2011), measuring EAEs observed on the Temple of the Feathered Serpent (TFS), the Pyramid of the Sun, and the Pyramid of the Moon in Teotihuacan.

Giner-Robles et al. (2022) proposed the use of Structural Geology for measuring the seismic pattern and building oriented-damage (BOD), for an instrumental earthquake that took place in Lorca (SE of Spain) in 2011 (M 5.3), generating significant damage in buildings of different architecture. Also, the method allows us to establish the orientation of the seismic ray direction (SSD). In this work, these authors represent the EAEs in stereogram plots by using a Schmidt lower hemisphere net (Lambert azimuthal equal-area projection).

3. Teotihuacan culture and geographical location

Teotihuacan (100 BCE–650 CE) was one of the most influential cultures in the history of the Ancient America Complex, and one of the most relevant in the Mesoamerican zone (Manzanilla, 2005). The history of the city shows a turning point at the end of the 7th century, with a sharp decrease of the population and abrupt loss of geopolitical power in the dominant cultures (Moragas-Segura and Sarabia-González, 2007; Moragas-Segura, 2013; Manzanilla, 2015; Clayton, 2020).

Teotihuacan is a hinterland monumental city-state (Figs. 1, 2), covering an area of about 22 km^2 during its thriving period, with an estimated population about 100,000 (Millon, 1966, 1973). Some authors claim that the maximum population could reach up to 200,000 people (Matos-Moctezuma, 2009; Clayton, 2015). The city has some of the greatest pyramids from around the world: The Pyramid of the Moon (Sugiyama and Cabrera-Castro, 2007), the Pyramid of the Sun (Piña-Flores et al., 2020), and the Temple of the Feathered Serpent (Sugiyama, 1989; López-Austin et al., 1991, Fig. 2). Around these pyramids, many upper and medium class residential areas are clustered (Clayton, 2015; Nichols, 2020). The urban layout is arranged around a great avenue with N15°E trending, and is more than 2 km long (Avenue of the Dead, Fig. 2a and 2b). This axis changed from N-S to the present orientation of N15°E in the Miccaotli phase (Table 1). Teotihuacan is built on volcanic rocks in the northern part, and lacustrine sediments in the south (Fig. 2b).

The history of Teotihuacan is summarized by its cultural periods (Table 1). Beginning between the years 150 – 1 BCE, the flourishing of the Teotihuacan people is related to volcanic eruptions: the eruption of the Popocatepetl, and the destruction of Cuicuilco city-state in the Xitle eruption (250–300 CE, Siebe, 2000, 2004; Clayton, 2015; Manzanilla, 2015). Teotihuacan reached the maximum population between 100 and 200 CE, the Xolalpan, and Metepec phases (450–650 CE, Table 1). Eventually, from 550 CE a sharp decrease of inhabitants, fires, and collapsed buildings was reported by different authors (Manzanilla, 2015; Nichols, 2016, 2020; Clayton, 2020). This fact marked the beginning of the Epiclassic cultural Period in the central highlands of Mexico. The city abandonment is related to the exodus from Teotihuacan to the city of Xochicalco (Alvarado-León, 2015, Fig. 1 blue star), and the flourishing of a new culture in the emergent city of Tula (Toltec culture, Healan, 2012).

3.1. The Temple of the Feathered Serpent

This temple is included in the Citadel (Fig. 2), an architectural complex representing the sacred mountain and planet Venus (Gómez-Chávez, 2017; Gómez-Chávez and Gazzola, 2021). The temple consists of a quadrangular base of a six-level stepped pyramid built in a distinctive Teotihuacan style known as *tablero-talud* (Sugiyama, 1989; López-Austin et al., 1991; Cabrera-Castro et al., 1991; Sugiyama, 2005; Price et al., 2020), with an area of 126 m^2 approximately, and a height of 15 m. This type of widespread construction along with the contemporaneous Mesoamerican buildings (Gendrop, 1984), consists of a short stepped *talud* with an overhanging cantilever decorated with the head of a feathered serpent and headdress, in the case of the Temple of the Feathered Serpent.

The age of construction of the basement of the Old Temple of the Feathered Serpent (OT) was dated around 150 CE (López-Austin et al., 1991; Sugiyama, 2005). This building includes the sacred westward staircase, balusters, rafters, and was covered by a feathered serpent emerging from the petals of a flower, and a Tlaloc deity or headdress. Cabrera-Castro et al. (1991) pointed out that the OT was built during a

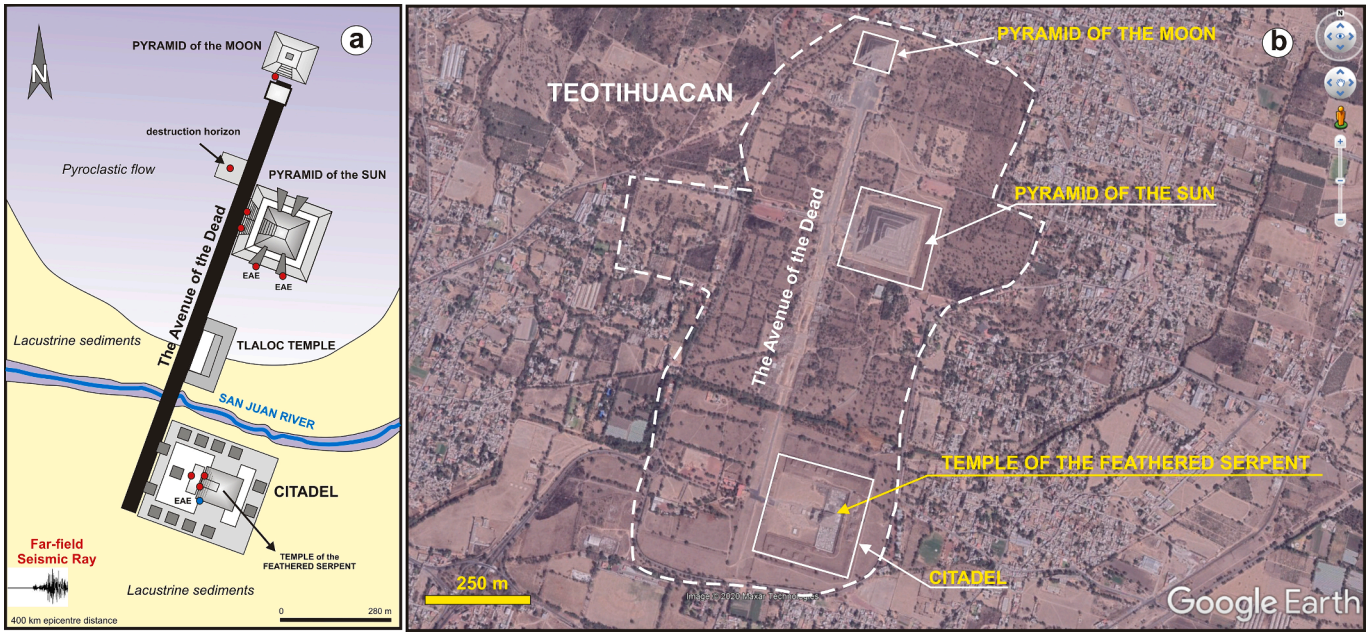

Fig. 2. Layout and plan view of Teotihuacan city. a. Plan view of the Teotihuacan archaeological site and pyramids and temples. Red and blue dots indicate the location of the Earthquake Archaeological Effects (EAE). The seismic ray (SSD) is assumed from a potential strong earthquake located at the Middle American Trench (MAT), in the west Mexican coast, and 400 km away of Teotihuacan city. The geology is from Chávez et al. (2001), with lacustrine (yellow) and pyroclastic Quaternary deposits (grey). b. Aerial view of the Teotihuacan archaeological site from Google Earth, image of 14th of January 2020. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Cultural Periods, main events and age of building monumental edifices in Teotihuacan. Timeline combined from Carballo (2007), Beramendi-Orosco et al. (2009), Sugiyama et al. (2013), Cowgill (1997), (2015), and Nichols (2016).

Mesoamerica chronology	*Teotihuacan Chronology*	*AGE*	*Main Events*
Early Colonial	Azteca IV	1521–1600 CE	Chieftain's setup in Teotihuacan.
Late Posclassic	Azteca II-IV	1450?–1521 CE	Otumba as city dominant in the basin.
	Azteca III	1350/ 1400–1450 CE	1420 Azcapotzacolco briefly conquered of Teotihuacan, 1428 Nezahualcoyotl dominance.
Middle Posclassic	Azteca II	1150/ 1200–1350 CE	Teotihuacan under the Acolhuas dominance.
Early Posclassic	Azteca I	900/1000/ 1150 CE	
	Atlatongo/ Tollan	1000–1150/ 1200 CE	
	Mazapa	900–1000? CE	Sharp decreasing of Teotihuacan people, power and cultural loss. Tula culture arises in the zone.
EPICLASSIC	Coyotlatelco	650–900 CE	The end of the Teotihuacan culture, Early EPICLASSIC/ Oxtotipac 600–700 (?). Culture of Coyotlatelco and local cave reoccupation.
CLASSIC	Metepec	550–650 CE	The beginning of the city collapse.
	Late Xolalpan	450–550 CE	Abandonment of the foreign neighbourhoods.
	Early Xolalpan	350–450 CE	The arrival of Strangers in Tikal (378). Pacific coast people interactions.
	Late Tlamimilolpa	250–350 CE	Desecration of Feathered Serpent Temple. Consolidation of urban departmental complexes.
	Early Tlamimilolpa	150–250 CE	Sun Pyramid early stage (170–310), Building 4 Moon Pyramid (200–300), The Feathered Serpent Pyramid (200–250). Beginning of outskirt neighbours (Oaxaca, Costa del Golfo, west México). First contact with Maya culture (200).
	Miccaotli	100–150 CE	Exponential growth of Teotihuacan people.
Late PRECLAS./ Early CLASS.	Tzacualli	1–100 BCE	Sharp and explosive inhabitants increasing of Teotihuacan. Urban layout according to 15°E and works on San Juan River (0–150).
Late PRECLASSIC	Patlachique	100–1 BCE	Beginning of Teotihuacan, people moving from south to north of the basin, and from Puebla valley. First stage of Moon Pyramid. Edification of Conjunto Tres Templos.
	Tezoyuca	200–100 BCE	Cuicuilco pottery.
	Cuanalán	650–200 BCE	Mexico Basin increasing inhabitants, the beginning of urban cities, Cuicuilco (500–100 BCE).
	Chiconautla	900–650 BCE	
Early/Middle PRECLASSIC	Altica	1150? –900 BCE	Small autonomous groups.

single phase of construction in Miccaotli or Early Tlamimilolpa times (~250 CE ± 50). It is believed that the political and religious centre of Teotihuacan was transferred to the Citadel Complex around Miccaotli – Early Tlamimilolpan times (Sugiyama, 1993), and the city was supposed to have entered its most stable period after about 350 CE, which lasted until the Metepec phase (650–750 CE, Table 1).

The blocks of the west staircase of both the Old and New Temple, are made of basalts (andesite), probably from non-local sources (Murakami et al., 2018), which implies a distant quarry, transportation, and a political relationship with other city-states. First, a low stone platform was built on the levelled *tepetate* (compacted soil ground) as a base for the OT. A new facade (*Adosada* platform), corresponding to a later construction phase, covers the west side and main staircase of the OT. The west sacred staircase is covered by a new structure which includes a different staircase to reach the top of the pyramid (Sarro, 1991). This later addition leads to the so called Feathered Serpent New Temple (NT). The *Adosada* platform has a west staircase with rafters and balusters, which is rather simple in comparison to the hidden and deformed west staircase of the Old Temple, and no feathered serpent and headdress sculptures were added.

3.2. The sacred pyramids of the Sun and the Moon

The Pyramid of the Sun at Teotihuacan (Fig. 2) has a height of 70 m, 10^6 m^3 in volume, and 230 m × 220 m of base. This is a monumental religious and political building with an architectural style of *tablero-talud* (Gendrop, 1984). Millon et al. (1965) suggested that the Pyramid of the Sun was constructed between the years 1 and 150 CE (early Tzacualli, Table 1), but the results from radiocarbon dating suggest that the construction of the complex (170–310 CE), and the subterranean tunnel (140–240 CE) are later than previously thought (Sugiyama and Cabrera-Castro, 2007; Sugiyama et al., 2013). The pyramid is a mud mound filled with fragments of *tepetate* and adobe bricks and stones, covered in a succession of *tablero-talud* facades, and enlarged at different phases (Sugiyama et al., 2013). Sugiyama et al. (2013) defined three phases of construction: (1) the pre-Sun Pyramid area (Phase I), consisting of three architectural units that were destroyed before the construction of the final monument. (2) Construction of the Pyramid of the Sun itself (Phase II), which consisted of a single construction building and phase, and (3) Phase III, construction of the west *Adosada* platform. In addition, the area suffered other minor construction modifications through time.

The Pyramid of the Moon (Fig. 2) is a quadrangular pyramid with a 144 × 144 m^2 base, and 43 m in height. Excavations from Sugiyama and Cabrera-Castro (2007) have divided the building evolution into five stages with two pyramid enlargements from Building 1 (100 ± 50 CE), probably younger than the Pyramid of the Sun, to Building 7 (400 ± 50 CE). Once again, the constructive style is *tablero-talud*, with the main staircase located on the south facade. These authors pointed out that the west side was reconstructed and reinforced during the construction of Building 3 (225 ± 50 CE), associated to the destruction of a wall, and with an E-W edifice enlargement.

4. EAEs on the Teotihuacan pyramids

Several EAEs have been measured on the Temple of the Feathered Serpent (Old temple and New temple), and the Sun and the Moon pyramids (Fig. 2a) for this study. The most abundant are dipping broken corners affecting the basalts blocks in the west staircases of the Temple of the Feathered Serpent, and the Pyramid of the Sun (Fig. 3). For representing the EAEs orientation, we have used stereogram plots with the EAE orientation, measured as lines and planes, depending on the type of EAE and according to the methodology described by Giner-Robles et al. (2022).

The dipping broken corner (DBC) or chip marks (Stiros, 1996; Marco, 2008) is a triangular faceted shape generated by an oscillatory movement between blocks in masonry walls, columns, and staircases (Fig. 4). This oscillation between annexed blocks repeatedly hits and breaks the corner, dipping the internal friction angle of the lithology (Fig. 4.2, 4.3, Rodríguez-Pascua et al., 2011). Also, displacement and tilting of blocks masonry and staircases is commonly observed due to seismic loading (i.e Rodríguez-Pascua et al., 2020). Experimental works using a shaking table provide the same effect of brick displacement and rotation in reinforced soil walls, showing a similar deformation pattern (Li et al., 2021).

In the case of Teotihuacan, a new type of EAE is observed, the "floating dipping broken corner, FDBC". This EAE affects the decorative overhanging blocks of the walls of the Old Temple of the Feathered Serpent (Fig. 4.4), arranged as *tablero-talud*. This EAE is also generated by the horizontal shaking related to seismic loading, generating a free-oscillation between blocks, hitting the external lateral side, and breaking the external corner. The joint between blocks is dry (i.e. without mortar), which facilitates the lateral shaking between annexed blocks. This block deformation and rupture is difficult to associate with deliberate destruction since it does not change the sculpted religious representation. Also, DBC and FDBC show one dominant oriented broken corner which suggests the oscillation of the blocks starts from a specific direction (Fig. 3). Furthermore, several hundreds of years are not enough for basalt weathering, plus the weathering usually generates rounded and exfoliated blocks (Viles et al., 2018).

4.1. EAEs on the Temple of the Feathered Serpent

The first description of the damage affecting the facade of the Feathered Serpent Old Temple was from Sugiyama (1989). As a consequence of the destruction, the west staircase was covered by a new facade (*Adosada* platform), conforming to the Feathered Serpent New Temple. The original west staircase (Fig. 3) was reconstructed with concrete and volcanic blocks, although it was covered by another facade. One of the figures located at the lowest part of the staircase balusters (rafters) was damaged and replaced, which can be interpreted as a potential stone extrusion from seismic loading.

The staircase of the Old Temple of the Feathered Serpent is a masonry andesitic block with dry (cohesionless) contacts. Staircase blocks arranged as a running bond on a sandy base hit the vertical sides of each other from the seismic shock direction (SSD), causing the block corner to break.(Pérez-López et al., 2010, 2019; Pérez-López, 2012). Overturned, displaced, and tilted blocks are also found (Fig. 5). The spatial distribution of the EAEs is mainly located on the west side of the OT and NT (Fig. 3). The EAEs observed in the west facade of the Old Temple are floating dipping broken corners (FDBC, Fig. 3c, 3d, and 3f).

A total of 123 dipping broken corners (DBC) planes were identified but only 22 plane measurements were obtained due to access restrictions by renovation works. Most of the dipping broken corners appear in the north corner of the stair steps (Figs. 3 and 5), and the three lower rows of the west staircase of the *Adosada* platform (Figs. 3e, 3f, and 5). Overturned and displaced step blocks appear in the first five rows of the staircase (Figs. 3e, 5c, 5e). Floating dipping broken corners appear mostly in the west facade, affecting the hanging blocks that bound the sculptures of the feathered Serpent and the headdress (Figs. 3c, 3d, 5, and 6). They mainly appear in the hanging north corner, showing the same spatial pattern as the DBC observed in the old and new Temple of the Feathered Serpent staircase (Fig. 6). Also, FDBC appears in the south facade of the Old Temple (Fig. 3f), affecting the bottom side of the decorative blocks bordering the headdress figure, and oriented to the west. Fig. 7 shows the main orientation of the EAEs by using the stereogram plots, planes of the dipping broken corners and the different monuments. Green and red arrows indicate the sense of vibration for generating these EAEs. Most of the FDBC appears at the bottom part of the blocks and is oriented to the north on the west side and to the west on the south side (Figs. 7, 8). This implies that the origin of this deformation is due to horizontal shaking instead of other causes like falling blocks from upstairs or weathering erosion.

The stereogram of DBC shows a NW-trend (N335°E) of the dipping sense, corresponding to the rupture of the north corners of the west staircase and floating masonry blocks, and a secondary mode of SW corresponding to the south corners (Fig. 7). The spatial distribution of EAEs in the Old Temple and New Temple (Fig. 8) concurs with a seismic ray coming from SW, from the Middle American Trench (220° ± 10°). This area is prone to trigger megathrusts of magnitude $M > 8$ and 8.5 (Suarez and Albini, 2009). We also measured DBC at the oldest pyramid of the citadel, showing a NE trend. These data correspond to the first row of the staircase on the south side of the ancient pyramid.

Fig. 9 shows the internal friction angle of basalts affected by shear rupture obtained from González de Vallejo et al. (2008) and Miranda et al. (2018), in comparison with the dip angles obtained from the dipping broken corners in the buildings of Teotihuacan. This reinforces the main argument of strong horizontal shaking to explain the corer rupture in stair steps and floating masonry blocks.

The principal dip-sense of the total set of DBC and FDBC is towards NW, with a secondary striking towards SW (Fig. 9B). This direction suggests that the seismic ray came from the SW, affecting the W blocks of the staircase and overhanging decorative blocks of the Old Temple, and affecting the S facade less. The same deformational pattern is observed in the W facade of the Pyramid of the Sun at the *Adosada* platform. The dip of the triangular facets measured from DBC is mostly 60° (Fig. 9A), which concurs with the angle of internal friction for andesitic (basalts) blocks with brittle rupture (González de Vallejo et al., 2008, Miranda et al., 2018).

4.2. EAEs on the Sun and Moon Pyramids

The Sun and Moon Pyramids experienced strong repetitive earthquakes throughout their entire life (c.a. 100 CE to present), according to the high tectonic activity in the Mexican subduction zone. Examples of similar shaped pyramids that were affected by earthquakes are described in Khalil et al. (2017). Sugiyama et al. (2013), pointed out the destruction of the Pyramid of the Sun during the pre-pyramid phase, at the early stages of construction (Tzacualli period, 1–100 yr. CE). (a) *Phase I – Pre-Sun Pyramid* (0–100 CE, Tzacualli). In this phase Millon et al. (1965) described an early structure wall consolidated (Fig. 10A), which was totally destroyed as pointed out by Sugiyama et al. (2013). The aforementioned authors also described other contemporaneous structures: Floor 2, with a destruction layer of many fragments of broken pottery of unknown origin; and Structure 1, featured by walls with a pattern of destruction affecting free-standing walls. (b) *Phase II – Sun Pyramid Construction* (150–200 CE, Early Tlamimilolpa). No evidence of destruction layers is described. (c) *Phase III – Adosada platform (post-250 Tlamimilolpa)*. Sugiyama et al. (2013) described a post-phase 2 and the destruction of a structure built before the *Adosada* platform, of which there are only remains of the foundation blocks. These authors suggest that the frontal part was taken-off and covered by the *Adosada* platform, similar to the Temple of the Feathered Serpent. Later, the *Adosada* platform was enlarged and reinforced several times by the *teotihuacanos*. A potential earthquake could be placed at Phase I, associated to the N-

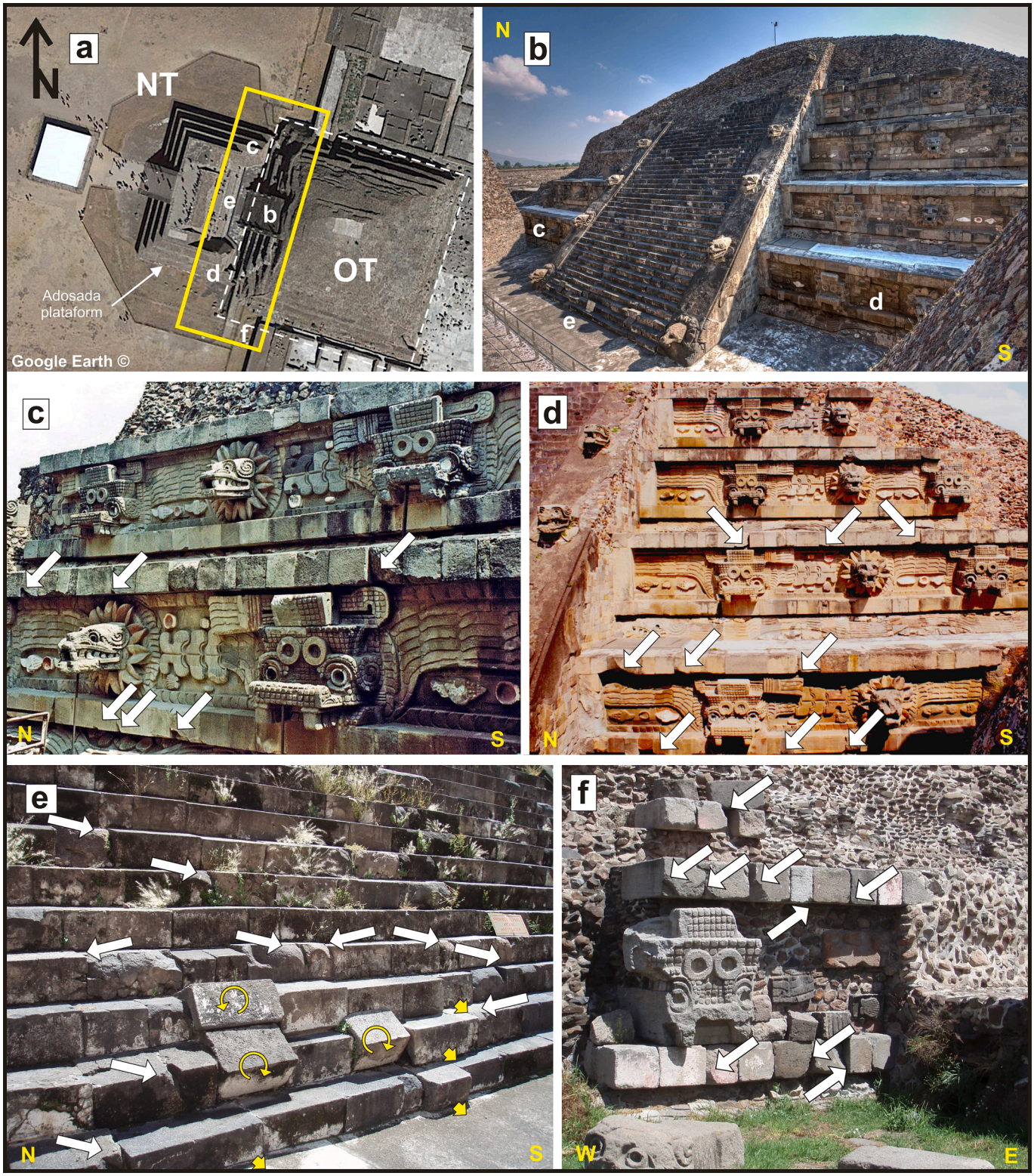

Fig. 3. Spatial distribution of the Earthquake Archaeological Effects (EAEs) in the Feathered Serpent Temple (OT, Old Temple and NT, New Temple). a. General plan view of the pyramid. b. West staircase of the OT, c. and d. West facade of the OT. e. Block rotation (yellow), block extrusion (yellow arrows), and broken corners (white arrows) affecting the principal staircase of the west facade of the Old Temple. f. Floating dipping broken corners affecting the south side of the OT of a headdress sculpture. See text for further explanation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

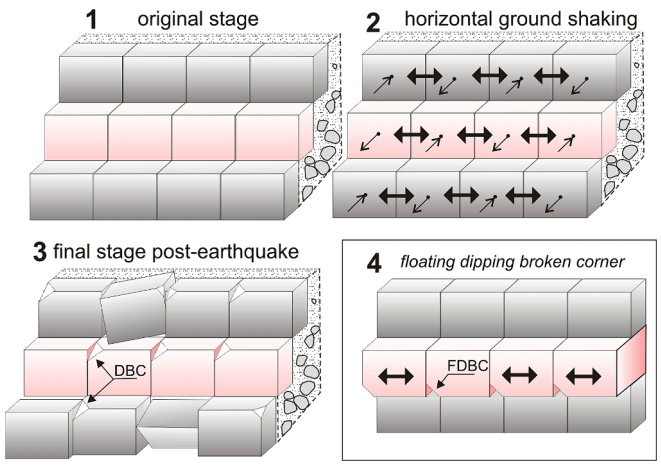

Fig. 4. Genesis of the dipping broken corner (DBC) and floating dipping broken corner (FDBC) affecting the staircase of the Old Temple of the Feathered Serpent. 1. Original staircase construction of andesitic blocks. 2. Horizontal shaking from earthquake and perpendicular movement from seismic waves. 3. Final stage with predominant dipping broken corner (DBC) formation at the left upper corner of the andesitic blocks. 4. Sketch of the "floating dipping broken corners", (FDBC) observed in the decoration of the west and south sides of the Old Temple.

trending wall tilting described by Millon et al. (1965), (Fig. 10A). Additionally, two potential earthquakes could be identified at Phase III, one phase of destruction before the *Adosada* platform was built and another, afterwards, bearing in mind that DBCs were observed at the first row of the *Adosada* staircase. The latest earthquake could be responsible for the EAEs observed at the west staircase of the *Adosada* platform at the Pyramid of the Sun. The staircase consists of andesitic blocks with a predominantly broken corner in the north corner of the block. The dipping plane shows a NW-trend (Fig. 7).

Piña-Flores et al. (2020) have studied the geological setting of the Pyramid of the Sun and modelled the seismic response of earthquakes larger than M 6. Their model shows a low-velocity anomaly in the SW part of the pyramid, in consonance with the zone where the EAEs appeared. Besides, there is a peak of amplitude for a frequency of about 0.5 Hz for the top and the basement of the pyramid, and between 4.5 and 5.5 Hz in the first level, the zone where the DBC appeared. The presence of large surface cracks in N and S walls could be related to the presence of counterforts to avoid the buildings seismic oscillation.

Seven different construction phases of the Pyramid of the Moon have been identified from superimposed structures (Sugiyama and Cabrera-Castro, 2007, Fig. 10B). We have used the date of construction estimated by Sugiyama and Cabrera-Castro (2007) as a "post-quem" date. The upper section destroyed in Building 1 (100 ± 50 CE), the facade destroyed and a platform added to the west face in Building 3 (225 ± 50 CE), suggests a potential seismic shock direction between N-S and N45°E. Building 4 (250 ± 50 CE) shows an apparent north wall

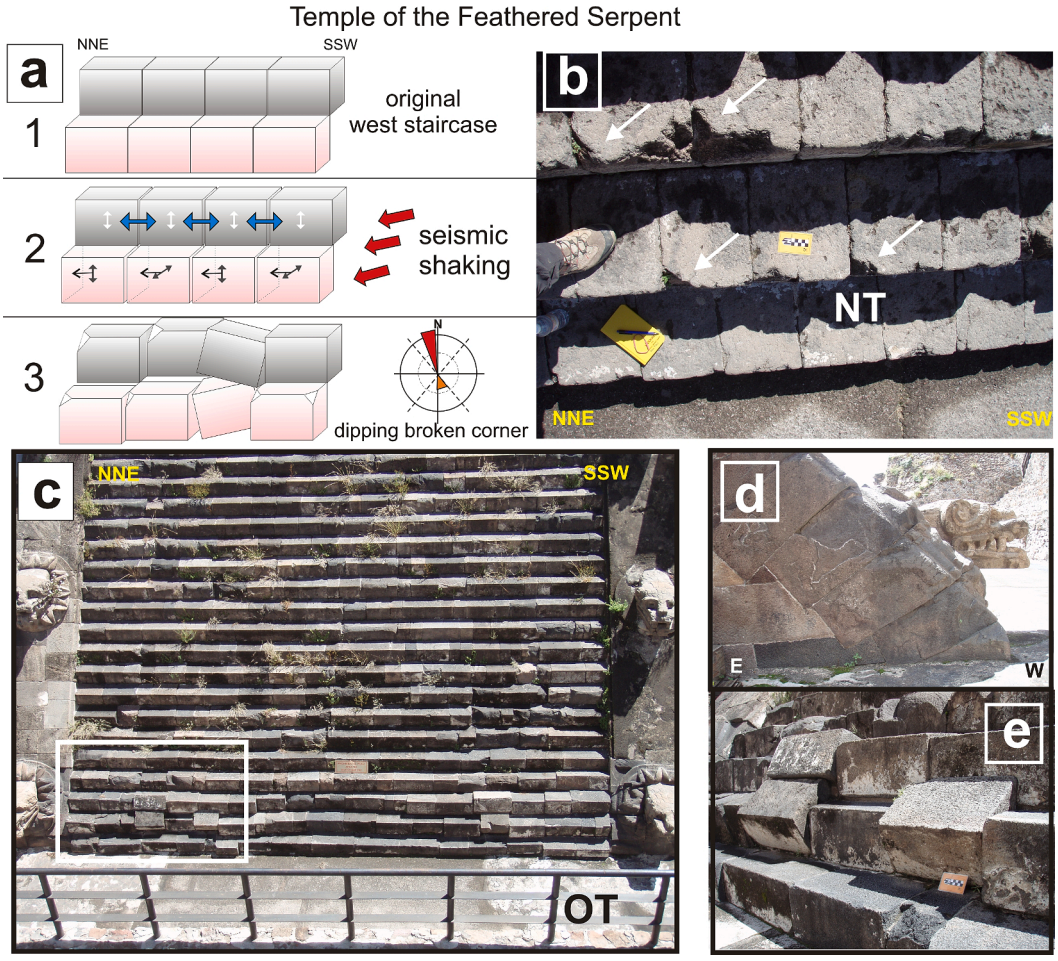

Fig. 5. Floating dipping broken corners affecting the Old Temple and the New Temple. a. Conceptual model. b. Detailed photograph of the dipping broken corner (white arrows) affecting the first row of the west staircase of the New Temple. c. Front view west staircase of the Old Temple. d. Lateral view of the north balusters (rafters) of the west staircase of OT showing imbricated blocks. e. Rotated and overturned blocks in the lower part of the west staircase of the Old Temple (white rectangle).

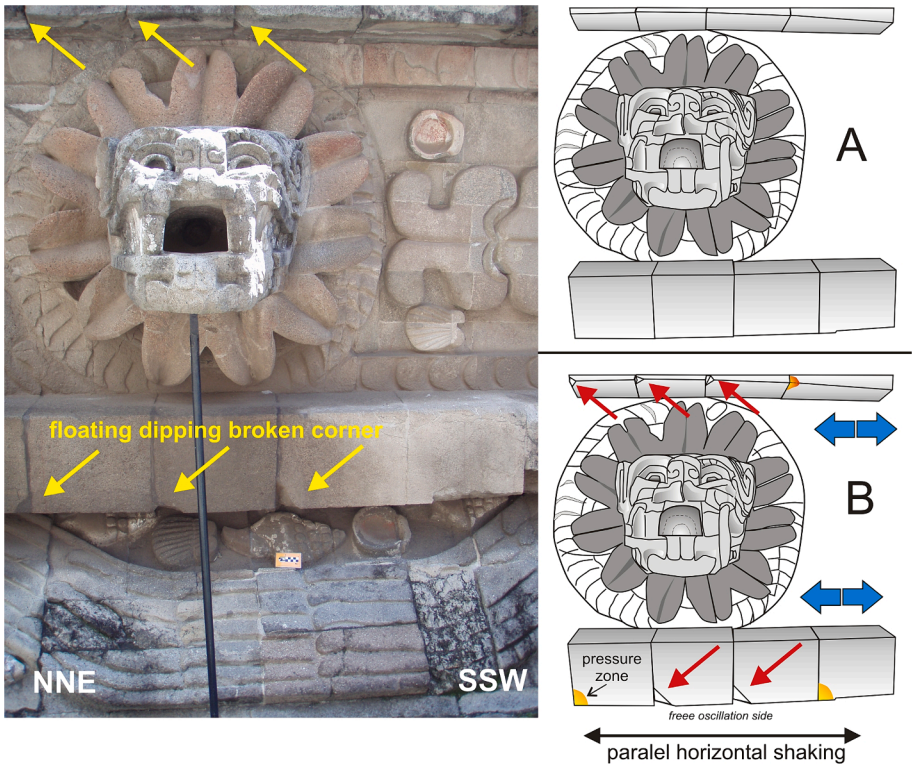

Fig. 6. Detailed view of the dipping floating corner (yellow arrow) affecting the west facade of the Old Temple, related to the attached blocks of a feathered serpent head sculpture. Floating Dipping Broken Corners appear to be mainly at the bottom side of the blocks and oriented northward. This pattern suggests seismic loading from south, southwest to north, northeast. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

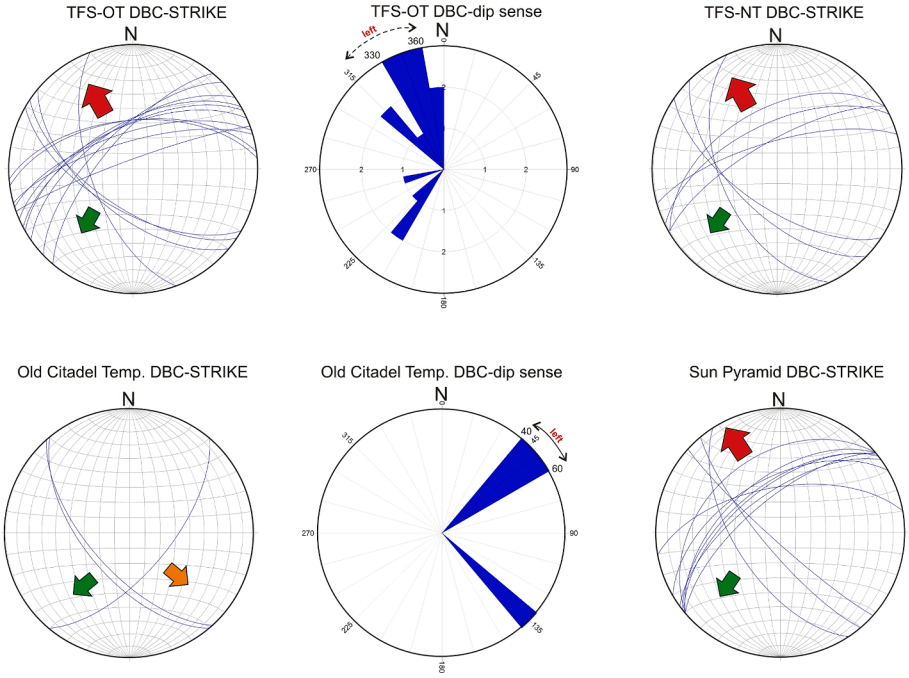

Fig. 7. Stereograms of the strike (left, lower hemisphere, Schmidt net, equal area), and rose diagrams of the dip sense (right), of the dipping broken corners measured at the west facade of the New and Old Temple staircase, the Old Citadel temple and the Pyramid of the Sun. Red arrows indicate the NW dip sense, green arrows SW and orange arrow SE. Left side of the N-S staircase bricks is also indicated. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

destruction, probably related to the beginning of Building 5's construction (300 ± 50 CE). Building 7 is the current restored pyramid, and it was constructed 400 ± 50 CE. The first row of the south staircase of Building 7 is slightly folded. Unfortunately, the staircase was remodelled. Dates for each building's construction were obtained with ^{14}C and the abundance of pottery fragments in different burials (Sugiyama and

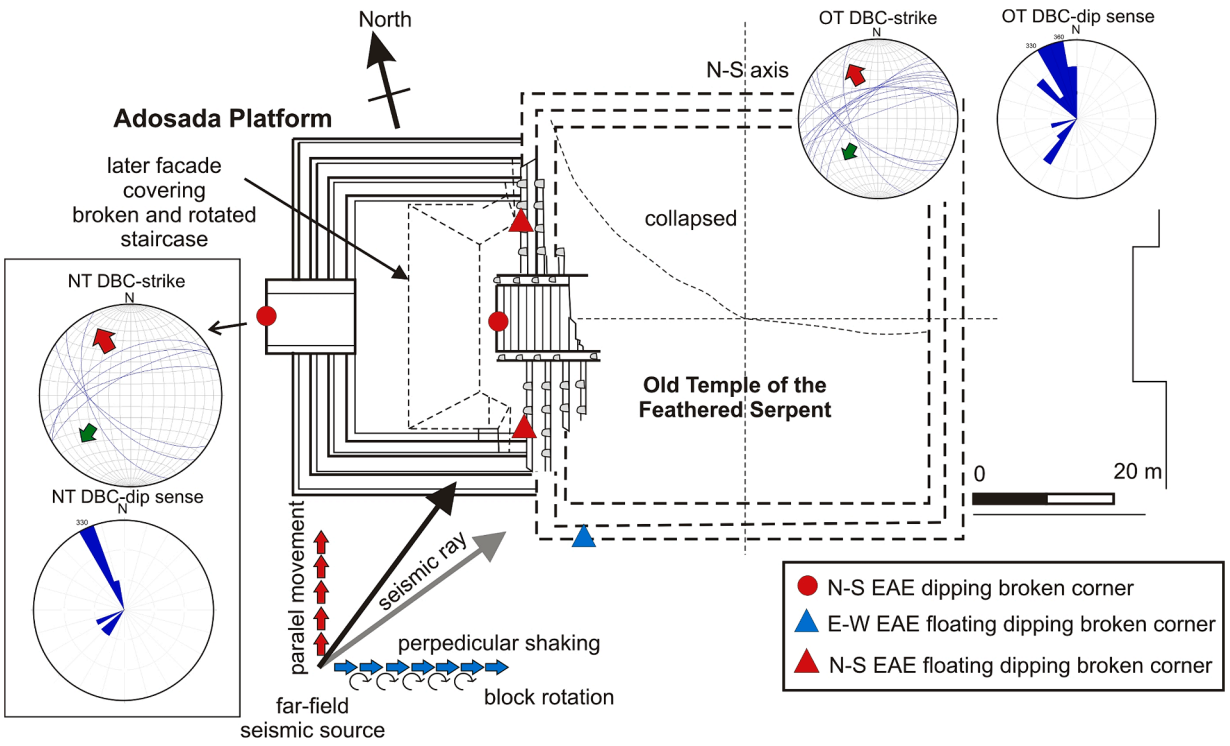

Fig. 8. Detailed plan view of the Feathered Serpent Old Temple (after Cabrera-Castro et al., 1991). The seismic shock direction from a megathrust is composed of two main movements affecting the west-staircase: red arrows indicate parallel shaking of the blocks of the staircase and generating normal and floating N-S dipping broken corner and blue arrows indicate perpendicular shaking, rolling the blocks and generating E-W dipping broken corners in the south corner. Stereograms of the broken side of the N-S dipping broken corners Old and New temple. Rose diagram of the main perpendicular vectors of the dipping sides. The stereogram representation is the lower hemisphere of Schmidt net, showing NW and SW trend. The rose diagram shows a NE trend for the striking of dipping broken corners. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Cabrera-Castro, 2007).

A stratigraphic sequence of different building phases at the Pyramid of the Moon is interpreted in Fig. 10B. A structure of stepped *talud* (S_0) is related to the early construction of Building 2 (Fig. 10B, Miccaotli, c.a. 150 CE); S_1, Building 3, was interpreted as a destruction layer by an earthquake; infill of interlayered fragments of *tepetate*, pottery and silty and sandy deposits related to water laid, and finally, S_2 (Building 4), a deformed and fractured wall (Fig. 10B).

5. Ancient Earthquake Source Model

The main source for megathrust earthquakes affecting the Mexican state is the Middle American Trench, with potential fault segments for triggering earthquakes larger than M 8.5 (Schellart and Rawlinson, 2013). The Mexican earthquake catalogue from 1787 (Sawires et al., 2019), shows 56 earthquakes larger or equal to M 7.5; 11 of them larger than M 8, and one earthquake of M 8.6, all of them related to the MAT dynamics (Fig. 1, red dots). Hence, an earthquake of magnitude larger than M 8 occurs in Mexico approximately every 23 years according to a naïve statistic. Also, intraplate earthquakes of M 7 located within the central part of Mexico cannot be ruled out (Langridge et al., 2000; Rodríguez-Pascua et al., 2017). Consequently, we propose two potential seismic sources: (1) a far-field seismic source-type, earthquakes similar to the Michoacan of 1985 (Anderson et al., 1986), and (2) intraplate near-field earthquakes (cortical earthquakes, similar to the Acambay earthquake 1912 M 6.9–7.0, Rodríguez-Pascua et al., 2017). Unfortunately, we have no evidence for discriminating one from the other, or the possibility of a combination between both sources, nor whether one of them prevails over the other. Furthermore, the objective of this work is not the determination of the seismic source of ancient earthquakes affecting Teotihuacan but the timeline of ancient earthquakes related to building damage and the Teotihuacan culture response instead.

6. Discussion

The architectural style of the pyramids, of quadrangular base and stepped facades, resist seismic loading quite well (Khalil et al., 2017), and only the external elements could be affected by horizontal shaking. Oriented collapsed walls have been described previously and not all collapses were associated to earthquakes. Only oriented wall collapses on the west and south facades have been considered, taking into account the orientation of the seismic ray NE-SW. A slight weathering of basalts affected those buried staircases during the abandonment stage (Sun pyramid and *Adosada* platform of the Quetzalcoatl temple, Fig. 5b), showing a rounded corner. However, the west staircase of the Old Temple covered shows freshly chipped corners due to the protection against burial and soil covering.

The possibility of weathering as a cause for chipped corners is discarded considering two main facts: (1) the natural chemical weathering and exfoliation need a long period of time and soil covering (~1 mm/1kyr, Viles et al., 2018), that could be accelerated by arid climate conditions and salt crystal growth, and (2) the centimetric breaking forming a triangular shaped plane close to 60° of dipping angle, concurrent with the inner friction angle for basalts (andesite, Fig. 9). Experiments on basalts with weathering performed by Tuğrul and Gürpinar (1997) show that weathering fractures in basalts in general show clayey laminae on the breaking surface, not observed in Teotihuacan. The climate conditions during the chipped corners are dry (Kennett and Marwan, 2015) and not the best for causing basalt decomposition. Hence, the simplest explanation for oriented dipping broken corners (brittle rupture) affecting west facades and tilted massive blocks is a seismic loading with horizontal shaking between annexed blocks without mortar.

We have determined the number of earthquakes by comparison of different EAEs and building damage (Fig. 11). The main dating source used by the archaeologists in Teotihuacan comes from a combination of

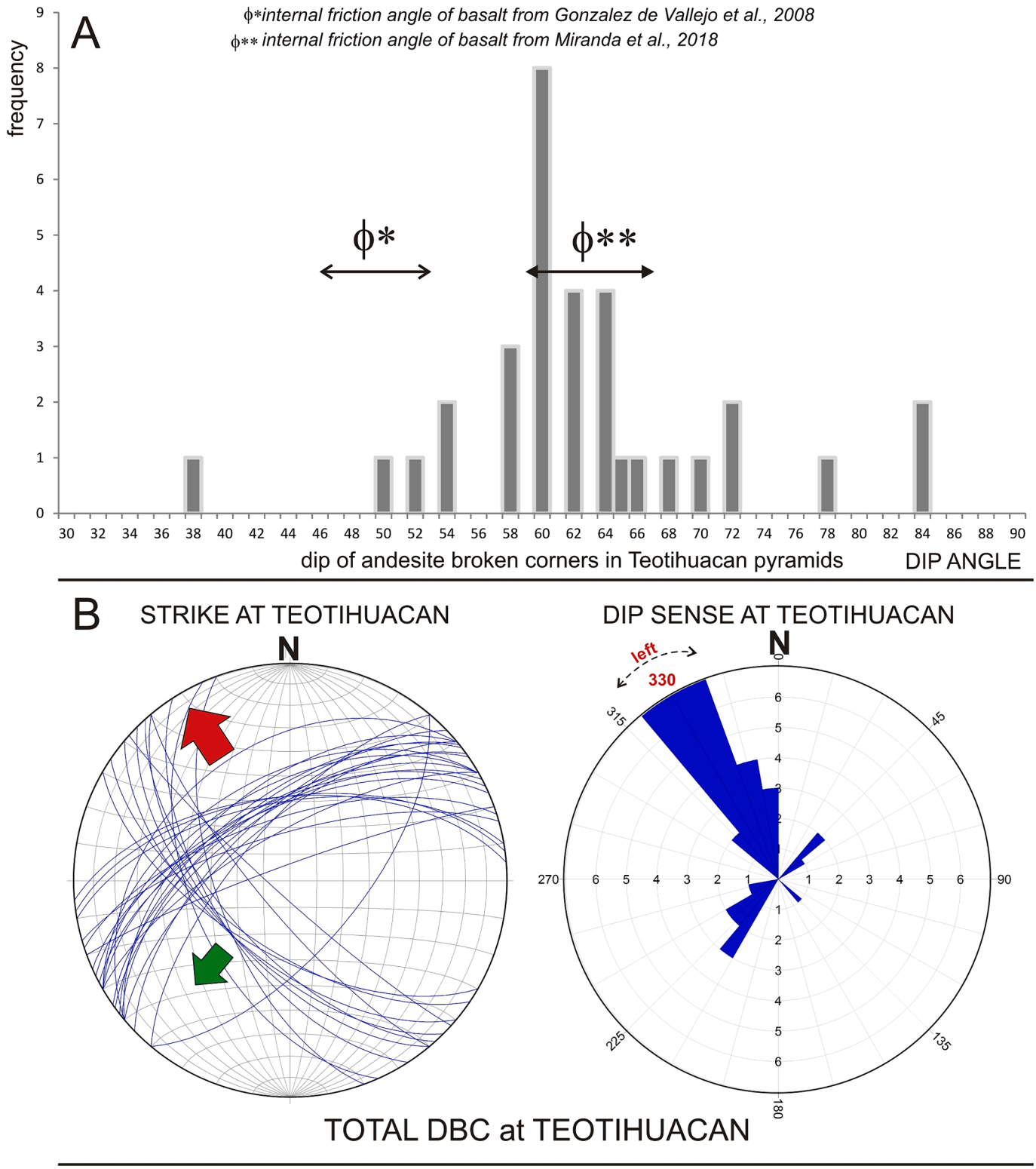

Fig. 9. Dipping broken corner (DBC), dip angle and dip sense. A. Frequency of dip angles of the staircase at the Pyramid of the Sun, the Temple of the Feathered Serpent, and internal friction angle from experimental failure test in basalts. B. Stereogram of the total DBC measured at Teotihuacan. Total Rose Diagram of the dip sense of the faceted planes (DBC). The main direction (NW) corresponds to the DBC measured in the left corner of the blocks in the west staircases.

analytical techniques and typological study of materials (i.e. Rattray, 1991).

Ancient earthquake 1: Tzacualli – Miccaotli period (~100 ± 50 CE), destruction level affecting the Pyramid of the Moon (Millon et al., 1965, Sugiyama, 1989, Sugiyama and Cabrera, 2007), and the pre-Sun structure by Sugiyama et al. (2013) (Fig. 11). We have assigned macroseismic intensity VIII-IX according to the work from Rodríguez-Pascua et al., 2022, based on the degree of destruction affecting at least two major buildings, Moon and Sun, with wall collapses, destruction of the top, and affecting the structure pre- Temple of the Feathered Serpent. This assignment is similar to the evaluation of MMI and EMS98 macroseismic scales.

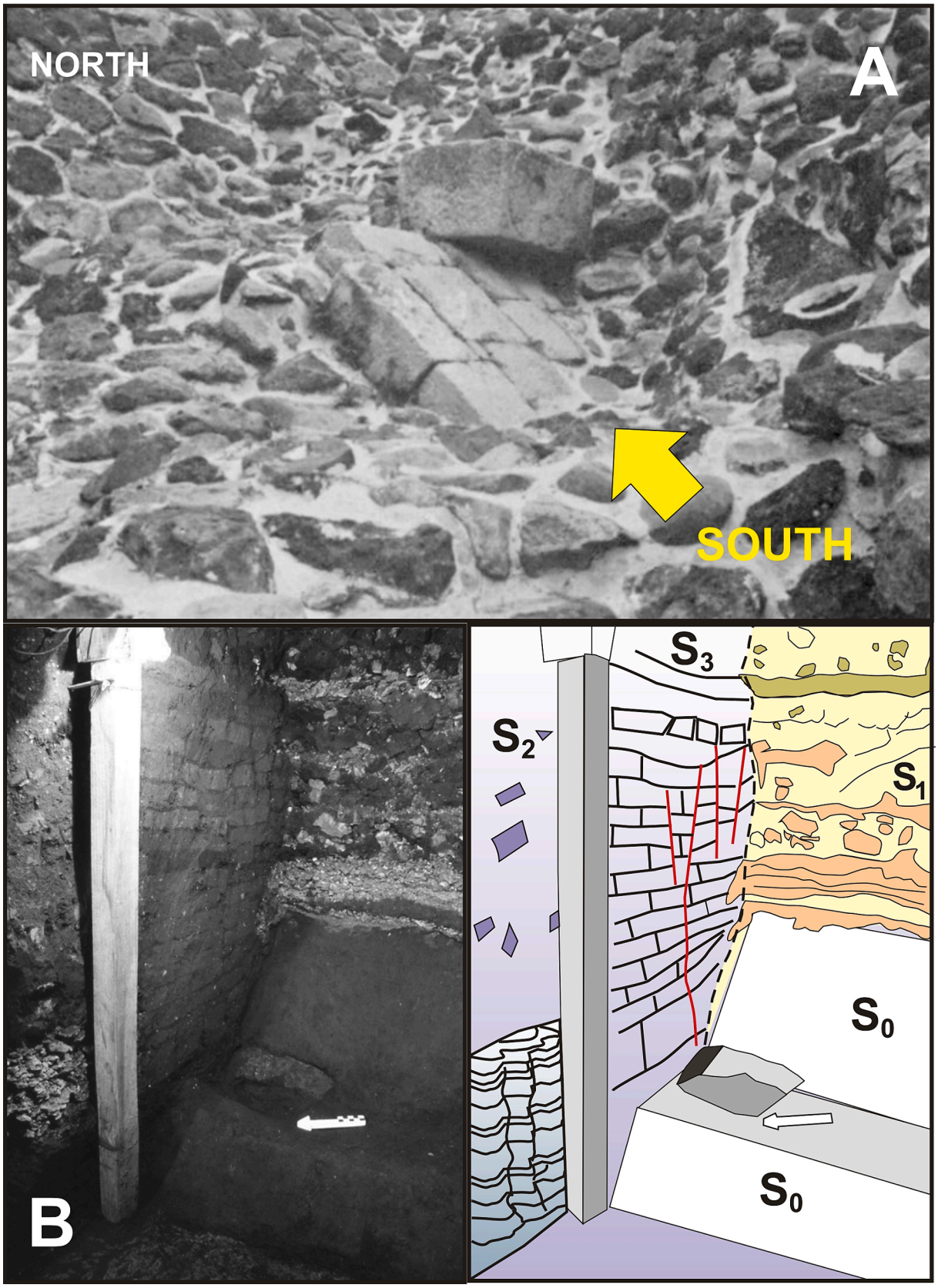

Fig. 10. Evidence of collapsed structures in the Teotihuacan pyramids. A. Collapsed and oriented wall of remain "*tablero-talud*", located at the south part of the *Adosada* Platform in the Pyramid of the Sun (after Millon et al., 1965). B. (left) Collapsed wall at the west side of the Moon Pyramid, covered by pottery and muddy layers, and covering another partially destroyed structure (after Sugiyama and Cabrera-Castro, 2007). (right) Interpreted infill of the west side of the Pyramid of the Moon, S_0: Original structure of Building 2; corresponding to a destruction level (Sugiyama and Cabrera-Castro, 2007); S_1: interlayered muddy and pottery layers showing soft-sedimentation and interpreted as Building 3. S_2 youngest layer with a deformed and fractured wall of Building 4. North is indicated by the white arrow.

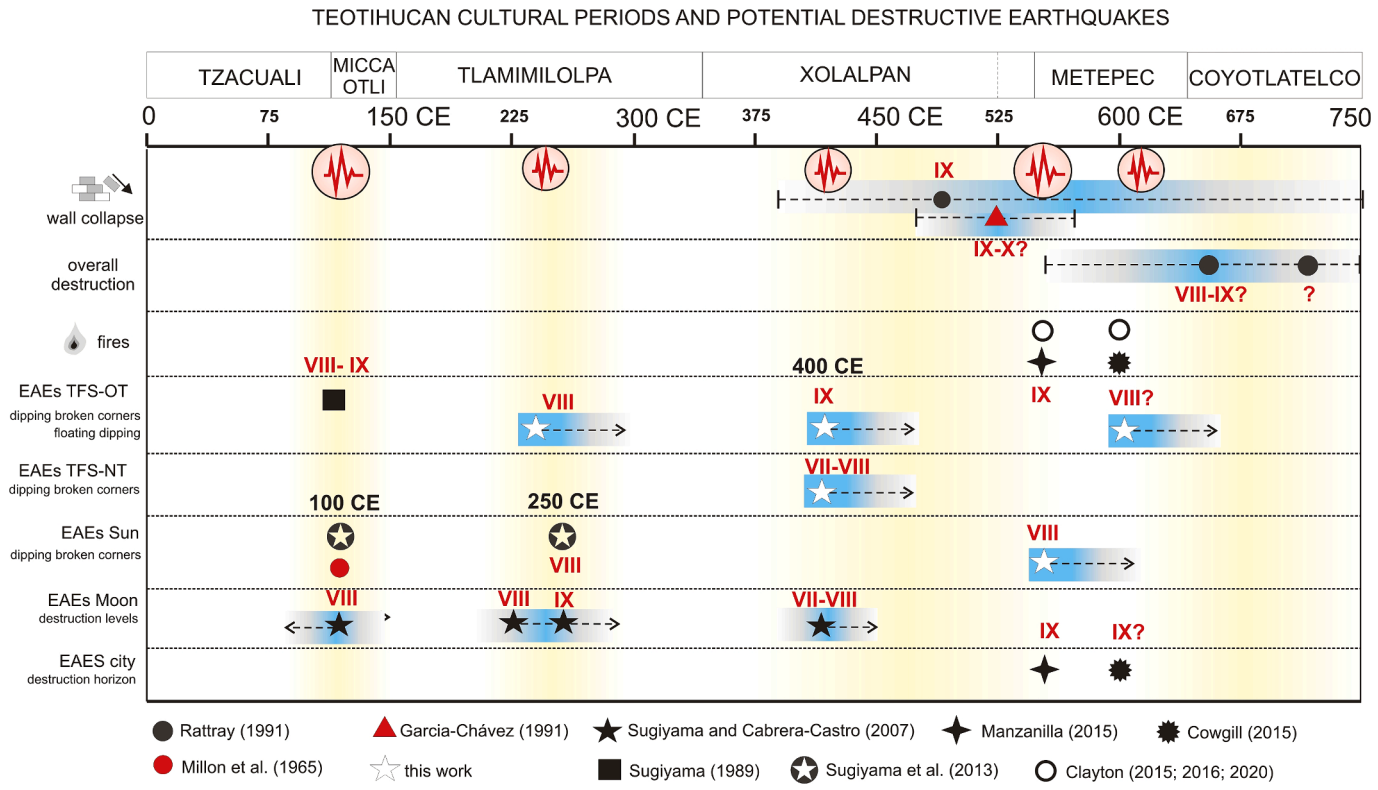

Fig. 11. Temporal distribution of the main EAEs observed at the Old Temple, New Temple and pyramids of the Sun and the Moon. Five historical destructive earthquakes have been identified. Error bars (blue and grey), come from different archaeological ages indicated in the legend. Intensities are estimated from the macroseismic archaeological scale proposed by Rodríguez-Pascua et al. (2022). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Ancient earthquake 2: Tlamimilolpa period (~225 ± 50 CE). DBC observed at the west staircase of the old Temple (Fig. 11), associated with tilted walls from Sugiyama and Cabrera-Castro (2007), affecting the Moon Pyramid (Sugiyama et al., 2013). Event affecting the three main buildings. In this case the assigned macroseismic scale from tilting walls is VIII although, it could reach IX. This intensity was lower than earthquake 1.

Ancient earthquakes 3 and 4: It is impossible to discriminate if there was one or were two ancient earthquakes, because archaeological dating shows a wide temporal range and EAEs could be assigned to the Xolalpan period (400 CE – 525 CE, Fig. 11). Rattray (1991) dated a bone artefact (radiocarbon non-calibrated age), recovered from under a collapsed wall (intensity IX) in 480 ± 100 CE (Table 1, Fig. 11). Calibrating this age with intcal20.14c (Reimer et al., 2020), the bone could date from pretty well anytime between 382 and 774 CE – so of itself it is not very informative of phase. Since the OT, NT and the *Adosada* platform of the Pyramid of the Sun existed from 480 CE, it is impossible to assign the EAEs measured in these buildings to events 3 or 4. These events are the most damaging earthquakes with numerous dipping broken corners on floating masonry blocks (IX), ordinary dipping broken corners affecting steps in staircases (VII-VIII), destruction levels identified at the Moon pyramid (VII), fires (IX), massive wall collapses (IX-X) and multiple destruction horizons affecting the whole urban city. The *Adosada* platform added to the Old Temple of Quetzalcoatl was built after this/these events.

Ancient earthquake 5: in this case, the observed effects were the collapse of the city, fires, and destruction of the main buildings (Manzanilla, 2015; Clayton, 2016; Clayton, 2020). Cowgill (2015) and Clayton (2020) suggest the year 600 CE as the end of the Teotihuacan dominance in the central Valley of Mexico. The macroseismic intensity could be interpreted from the abandonment of the city, fires, and building destruction, although no EAEs have been associated with this last earthquake, except the possibility that the overall destruction of the west staircase of the Old Temple of the Feathered Serpent occurred after that side was covered by the *Adosada* platform. Inner revolts during 550 CE caused widespread fire, building destruction, and the entire replacement of the religious sculptures (Manzanilla, 2015). This could be reinforced by an earthquake, as an extra triggering factor. In general, well-documented works (i.e. Manning et al., 2017; Lee, 2018) show that natural catastrophes can trigger inner revolutions in social and political systems. The maximum macroseismic intensity (Fig. 11) ranges between VIII and IX, according to the different destruction effects (Rodríguez-Pascua et al., 2022).

Regarding the seismic shock direction, the far-field seismic source from the MAT concurs with the EAEs observed at Teotihuacan (Figs. 1, 12). The MAT as the potential source is reinforced by historical and instrumental earthquakes recorded in the central basin of Mexico. The 1985 Michoacan earthquake (M 8.1, Anderson et al., 1986) and the ground motion amplification response for a frequency of 0.5 Hz (in agreement with Piña-Flores et al., 2020), could explain the location and orientation of the EAEs. Conversely, the spatial pattern of the EAEs, clearly NE-SW oriented, also suggests that the seismic source could be located at the MAT.

Despite EAEs appearing in both the Temple of the Feathered Serpent and the Pyramid of the Sun, EAEs on the Temple are more severe than in the Pyramid of the Sun. This is based on the OT and NT base consisting in the alternation of lacustrine and alluvial sediments, with different *tepetate* ground levels. Besides, the saturated and shallow phreatic level amplifies the seismic ground vibration and generates the most severe EAEs in the Temple of the Feathered Serpent. The base sediments in the north part of the city are mainly pyroclastic flows (Fig. 2), with less amplification under seismic loading. If the Teotihuacan people deliberately destroyed the west staircase of the OT, they did not use the rotated and extruded blocks for the construction of the new *Adosada*

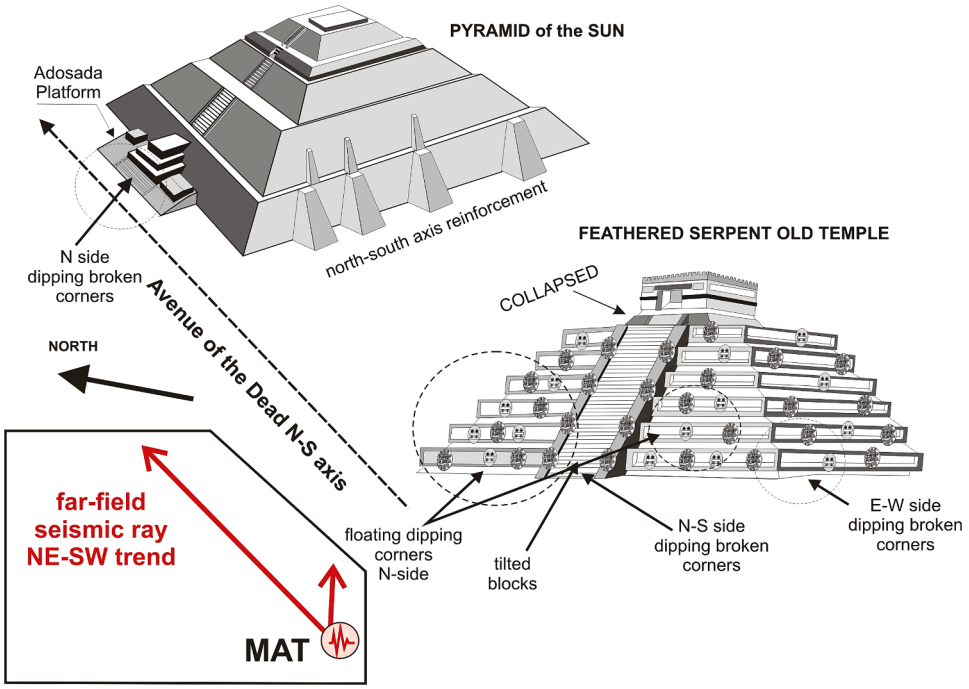

Fig. 12. Spatial location of EAEs in the west facades of the Pyramid of the Sun and the Temple of the Feathered Serpent, and estimation of the seismic ray direction (SSD) coming from far-field seismic source (red line, from MAT, SW of the city). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

platform. They covered and hid the tilted staircase using new blocks obtained from the commerce with outside neighbouring civilizations. This fact could be interpreted as a sign that they assigned a sacred or religious significance to the event that struck the city.

The ancient earthquake timeline for Teotihuacan presented here (Fig. 13), shows a combination of strong earthquakes and volcanic eruptions affecting the Central Valley of Mexico. High destructive macroseismic intensity could be associated with megathrusts of a magnitude larger than M 8 from the MAT and the site affected by the lacustrine infilling. The history of building reparations, enlargements, reinforcements, the presence of EAEs, and the use of new construction styles such as the *Adosada* platform, indicate the evolution of a culture living with strong earthquakes. However, the data are insufficient for estimating the magnitude of those earthquakes. Only the macroseismic intensities can be estimated and discussed.

Regarding the soil period of vibration associated to earthquake occurrence, it is true that far-field earthquakes generate a frequency of 0.5 Hz and near-field earthquakes generate higher frequencies (~1 Hz). The response of the soil in each case is different. However, in this work we have not analysed the soil response or carried out laboratory soil tests. This could be the future work for specialist to determine the differences between soil period and pyramid response to seismic ground motion.

One question that arises from this work is why later earthquakes have scarcely affected the Teotihuacan pyramids remains. Firstly, the seismic response of pyramids is related to their natural vibration period (Cacciola et al., 2022), as a dynamic response related to the structure–soil–structure interaction. Moreover, from 1787 to the present, eleven earthquakes of magnitude greater than M 8 has occurred in Mexico, and only one of them was greater than M 8.5 over 236 years. Looking back the catalogue of preinstrumental earthquakes from Suárez et al. (2020), the attenuation lines of macroseismic intensity sharply decreased with the distance, and intensities as large as VI could be reached for distances greater than 400 km. Hence, for reaching intensities greater than VI in Teotihuacan from subduction earthquakes, magnitudes equal or greater than magnitude M 9 are needed. Also, we have to bear in mind that buried archaeological remains are more stable for ground shacking that unburied buildings.

Prehispanic earthquakes are only referred to from prehispanic Codex and a macroseismic intensity scale was proposed by Garduño-Monroy (2016). Between the years 1460 CE to 1542 CE, 12 historic earthquakes are described (Suárez and García-Acosta, 2021) with intensities ranging between VI and X (Telleriano Remensis Code, described in Garduño-Monroy, 2016). Is interesting to note that Suárez and García-Acosta (2021) reported a strong historic cortical (intraplate) earthquake (1475 CE) affecting the Central Mexico basin, which demonstrated the possibility of a near-field seismic source. This earthquake could be related to high frequency seismic waves. These authors speculated that pre-Hispanic earthquakes could be greater than magnitude Mw 7.5 but this is not supported by documental information. The description of building damage could be related to a qualitative macroseismic intensity in the same way that we have done in this work. Historical intensities estimated from ancient writings are based on this idea. Therefore, the use of the intensities provided by Garduño-Monroy (2016) could approach a qualitative scale. Whatever the case, this pre-Hispanic catalogue suggests 12 strong earthquakes with intensities greater than VI affecting Mexico during a period of 82 years.

7. Conclusions

Evidence of earthquakes affecting the Teotihuacan city was found. Earthquake Archaeological Effects could be observed at the Temple of the Feathered Serpent (OT and NT), the Pyramid of the Sun and the Pyramid of the Moon.

At least, two strong destructive earthquakes (Intensity VIII-IX) affected Teotihuacan in the antiquity having a great impact on the development of the architectural styles. The first one occurred between the years 1–150 CE (Miccaotli phase), and the second one occurred in 455 ± 50 CE (Late Xolalpan-Early Metepec phase).

Another three damaging earthquakes (Intensity ≤ VIII) affected the area during the Tlamimilolpa phase (225 ± 50 CE), the Early Xolalpan phase (400 – 425 CE), and the Late Metepec phase (600 ± 50 CE). The

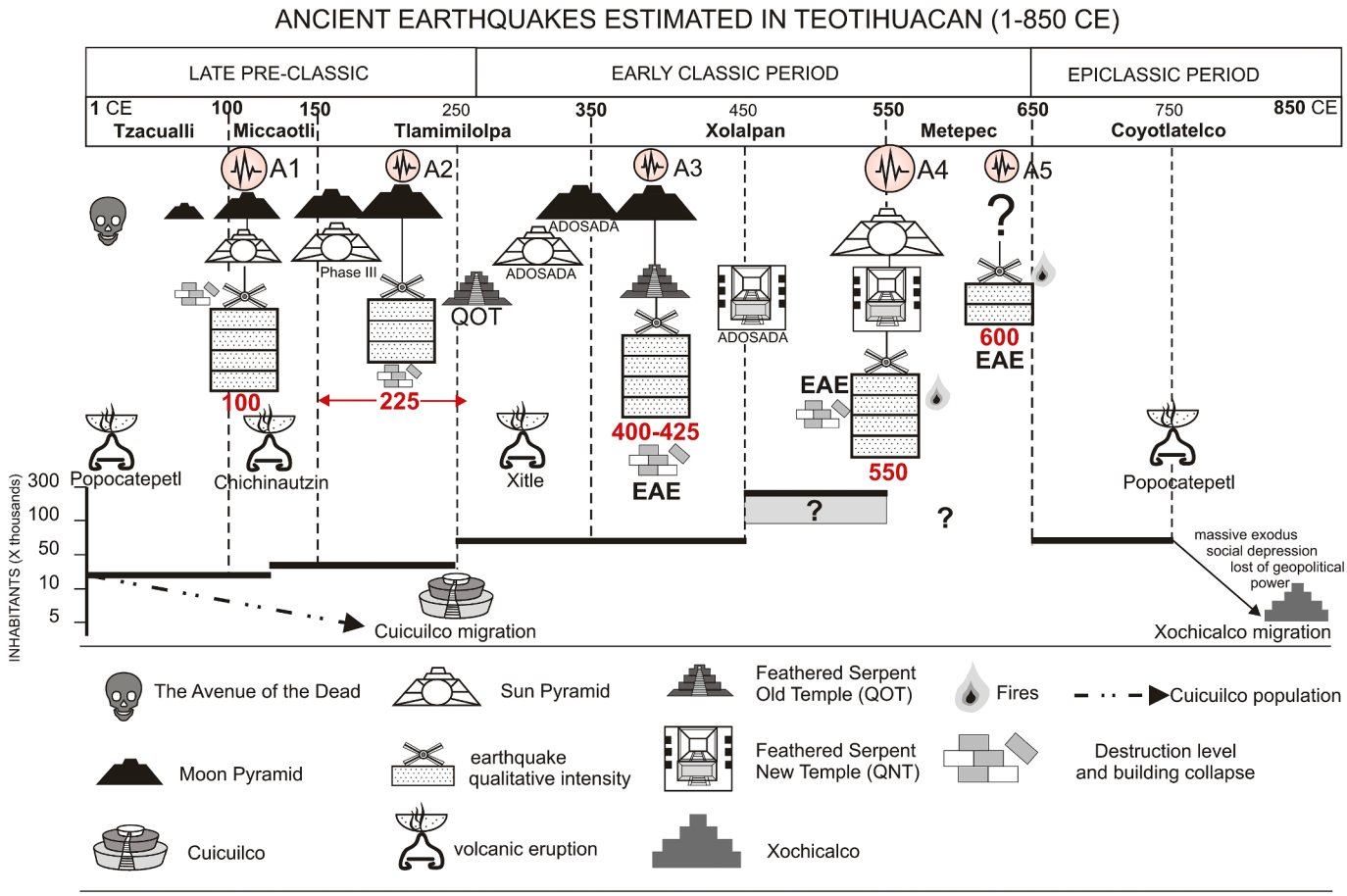

Fig. 13. Proposed time-chart for the interpreted main events during the timeline of the Teotihuacan. Five destructive earthquakes have been interpreted and represented by the Aztec intensity scale proposed by Garduño-Monroy (2016). The proposed ages of the ancient earthquakes are in red. Destruction of Cuicuilco, and the final migration to Xochicalco are included. The size of the pyramids indicates the age of enlargement and rebuilding. The volcanic eruption of the Xitle, Chichinautzin and Popocatepetl are included (after Siebe, 2000, and Siebe et al., 2004). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

conjugate action of ancient earthquakes can explain the archaeoseismic damage documented in the sites, but the last two earthquakes before its abandonment in c. 650 CE are the most likely cause.

EAEs described include brittle dipping broken corners affecting the west staircases of the Pyramid of the Sun and the Feathered Serpent Old and New Temple. We have introduced a new type of effect, the Floating Breaking Dipping Corner, which reinforces the theory of earthquake damage affecting the pyramids instead of deliberate human breaking or climate weathering of the basalts staircase stones.

The spatial pattern of the EAEs and the orientation of the DBC indicate a seismic shock direction from the SW to the NE. This means that the Middle American Trench could be the seismic source. In this case, a megathrust earthquake of magnitude larger than M 8 could explain the EAEs and the seismic intensity affecting the city. However, the possibility that a near-field earthquake was the seismic source cannot be discarded.

The combination of the high seismic energy released by repetitive earthquakes, the seismic frequency amplitude, and the Lake Texcoco sediments infilling could explain the deformation patterns observed in the pyramids and temples throughout the entire history of Teotihuacan. Finally, a comprehensive analysis of liquefaction and soft-sediment deformation of lake sediments from the Lake Texcoco could shed some light on the paleoseismic records affecting the central basin of Mexico.

Authors contribution

Raúl Pérez-López conceptualized the work, field work, data acquisition, archaeoseismology, formal analysis, original draft preparation, coordination, conclusions and figures; **Natalia Moragas-Segura** archaeological timeline, writing, investigation, tables, reviewing, discussing the conclusions; **Javier Elez** conceptualization, seismotectonics, maps, reviewing; **Pablo G. Silva** conceptualization, seismic acceleration, reviewing; **Jorge L. Giner-Robles** seismotectonics and earthquake analysis, reviewing; **Miguel A. Rodríguez-Pascua** field work, investigation; **Adrià Ramos** geology, reviewing; **María A. Perucha** field work; **Elvira Roquero** geology, and **Víctor Hugo Garduño-Monroy** funding acquisition, field work, archaeoseismology, investigation.

CRediT authorship contribution statement

Raúl Pérez-López: Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Natalia Moragas-Segura:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis. **Javier Elez:** Writing – review & editing, Methodology, Formal analysis, Data curation. **Pablo G. Silva:** Writing – review & editing, Supervision, Methodology, Formal analysis. **Jorge L. Giner-Robles:** Validation, Methodology, Investigation. **Miguel A. Rodríguez-Pascua:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Adrià Ramos:** Writing – review & editing, Validation, Supervision, Methodology. **María A. Perucha:** Validation, Formal analysis, Data curation. **Elvira Roquero:** Writing – review & editing, Validation, Supervision. **Víctor H. Garduño-Monroy:** Visualization, Validation, Project administration, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgments

This work was supported by the Project FAMRAD (PID2020-113407RB-I00) and is part of the research activities of PID2021-123510OB-I00 (USAL) AEI/10.13039/501100011033/ of the Spanish Ministry of Science; the Program Lost Cities funded by the Gerda Henkel Foundation (AZ 02/LC/20). We thank the Archaeological Council INAH (*Instituto Nacional de Antropología e Historia*, México) and Sergio Gómez-Chávez for consent to carry out the archaeoseismic analysis in the Sun and Feathered Serpent pyramids. Sadly and suddenly, the professor V. Hugo Garduño-Monroy and Dra. Elvira Roquero passed away. This was our latest work together and serves this publication with our warmest affection, as a posthumous tribute.

References

Alvarado-León, C.I., 2015. El espacio construido y los procesos de cambio en la Acrópolis de Xochicalco. Cuicuilco 63, 171–205. In Spanish.

Anderson, J.G., Bodin, P., Brune, J.N., Prince, J., Singh, S.K., Quaas, R., Onate, M., 1986. Strong ground motion from the Michoacan, Mexico. Earthq. Sci.. 233 (4768), 1043–1049. https://doi.org/10.1126/science.233.4768.1043.

Beramendi-Orosco, L.E., Gonzalez-Hernandez, G., Urrutia-Fucugauchi, J., Manzanilla, L. R., Soler-Arechalde, A.M., Goguitchaishvili, A., Jarboe, N., 2009. High-resolution chronology for the Mesoamerican urban center of Teotihuacan derived from Bayesian statistics of radiocarbon and archaeological data. Quat. Res. 71, 99–107. https://doi.org/10.1016/j.yqres.2008.10.003.

Cabrera-Castro, R., Sugiyama, S., Cowgill, G.L., 1991. The Templo de Quetzalcoatl Project at Teotihuacan: A Preliminary Report. Anc. Mesoam. 2, 77–92. https://doi.org/10.1017/S0956536100000407.

Cacciola, P., Shadlou, M., Ayoub, A., et al., 2022. Exploring the performances of the vibrating barriers for the seismic protection of the zoser pyramid. Sci. Rep. 12, 5542. https://doi.org/10.1038/s41598-022-09444-x.

Carballo, D., 2007. Implements of state power: weaponry and martially themed obsidian production near the moon pyramid. Teotihuacan. Ancient Mesoamerica 18 (01), 173–190. https://doi.org/10.1017/S0956536107000144.

Carballo, D.M., 2018. El desarrollo de la sociedad urbana en el Altiplano Central mexicano durante el Formativo y la transición al Clásico. Revista Española De Antropología Americana 47, 199–218.

Chávez, R.E., Cámara, M.E., Tejero, A., Barba, L., Manzanilla, L., 2001. Site Characterization by geophysical methods in the archaeological zone of Teotihuacan, Mexico. J. Archaeol. Sci. 28, 1265–1276. https://doi.org/10.1006/jasc.2000.0627.

Clayton, S.C., 2016. After Teotihuacan: A view of collapse and reorganization from the Southern Basin of Mexico. Am. Anthropol. 118, 104–120. https://doi.org/10.1111/aman.12522.

Clayton, S.C., 2020. The collapse of Teotihuacan and the regeneration of Epiclassic societies: a Bayesian approach. J. Anthropol. Archaeol. 59, 101203 https://doi.org/10.1016/j.jaa.2020.101203.

Clayton, S. 2015. Teotihuacan: An early urban center in its regional context. In: N. Yoffee (Ed.) The Cambridge World History (The Cambridge World History, pp. 279-299). Cambridge, Cambridge University Press. 10.1017/CHO9781139035606.017.

Cowgill, G.L., 1997. State and Society at Teotihuacan, Mexico. Ann. Rev. Anthropol. 26 (1), 129. https://doi.org/10.1146/annurev.anthro.26.1.129.

Cowgill, G.L., 2015. Ancient Teotihuacan. Early urbanization in Central Mexico. Cambridge University Press.

Garduño-Monroy, V.H., 2016. A proposal of a seismic intensity scale obtained from the Nahuatl Codex Telleriano Remensis. Arqueología Iberoamericana 31, 9–10. ISBN: 1989-4104 http://laiesken.net/arqueologia/. In Spanish.

Gendrop, P., 1984. El tablero-talud en la arquitectura Mesoamericana. Cuadernos De Arquitectura Mesoamericana 2, 5–28. In Spanish.

Giner-Robles, J.L., Rodríguez-Pascua, M.A., Pérez-López, R., Silva, P.G., Bardají, T., Roquero, E., Elez, J., Perucha, M.A. 2022. Geological structural analysis applied to archaeoseismology. In: Handbook of Cultural Heritage Analysis, D'Amico, Sebastiano, Venuti, Valentina (Eds.), Springer Nature Switzerland AG, pp: 1763-1778. ISBN: 9783030600150.

Giner-Robles, J.L., Rodríguez-Pascua, M.A., Pérez-López, R., Silva, P.G., Bardají, T., Grützner, C., Reicherter, K., 2009. Structural Analysis of Earthquake Archaeological Effects (EAE): Baelo Claudia Examples (Cádiz, South Spain). Instituto Geológico y Minero de España, Madrid, p. 130.

Gómez-Chávez, S., 2017. The underworld at Teotihuacan: the sacred cave under the Feathered Serpent Pyramid. In Teotihuacan: city of water, city of fire. In: Robb, M. (Ed.), Fine Arts Museums of San Francisco, De Young. University of California Press, San Francisco, pp. 48–55.

Gómez-Chávez, S., Gazzola, J. 2021. Spatial, Temporal and Symbolic Significance of the Myths Recreated in the Underworld and in the Space of the Citadel in Teotihuacan. In: Proceedings of an International Conference in Mexico, February 27-28, 2020, Matsumoto, Sugiyama, and García-Des Lauriers (Eds). Landscape, Monuments, Arts, and Rituals Out of Eurasia in Bio-Cultural Perspectives, 233-246 pp, Okayama. Japan.

González de Vallejo, L.I., Hijazo, T., Ferrer, M., 2008. Engineering geological properties of the volcanic rocks and soils of the Canary Island. Soils and Rocks 31, 3–13.

Guidoboni, E., 1989. I terremoti prima del Mille in Italia en elÍarea Mediterranea: storia, archaeologia, sismología. SGA-Instituto Nazionale di Geofisica, Bologna.

Hancock, P.L., Stewart, I.S., 2001. The Archaeology of Geological Catastrophes. Geol. Soc. Lond. Spec. Publ. 171, 45–70.

Healan, D.M., 2012. The Archaeology of Tula, Hidalgo, Mexico. J. Archaeol. Res. 20, 53–115. https://doi.org/10.1007/s10814-011-9052-3.

Kennett, D.J., Marwan, N., 2015. Climatic volatility, agricultural uncertainty, and the formation, consolidation and breakdown of preindustrial agrarian states. Phil. Trans. R. Soc. A 373, 20140458. https://doi.org/10.1098/rsta.2014.0458.

Khalil, A.E., Abdel Hafiez, H.E., Girgis, M., Taha, M.A., 2017. Earthquake ground motion simulation at Zoser pyramid using the stochastic method: A step toward the preservation of an ancient Egyptian heritage. NRIAG J. Astron. Geophys. 6, 52–59. https://doi.org/10.1016/j.nrjag.2016.11.003.

Kovacs, R.L., 2004. Early Earthquakes of the Americas. Cambridge University Press, p. 286 p..

Langridge, R.M., Weldon, R.J., Moya, J.C., Suárez, G., 2000. Paleoseismology of the 1912 Acambay earthquake and the Acambay-Tixmadeje fault, Trans-Mexican Volcanic Belt. J. Geophys. Res. 105 (B2), 3019–3037. https://doi.org/10.1029/1999JB900239.

Lee, H.L., 2018. Internal wars in history: Triggered by natural disasters or socio-ecological catastrophes? The Holocene 28 (7), 1071–1081. https://doi.org/10.1177/0959683618761549.

Li, S., Cai, X., Jing, L., Xu, H., Huang, X., Zhu, C., 2021. Lateral displacement control of modular-block reinforced soil retaining walls under horizontal seismic loading. Soil Dyn. Earthq. Eng. 141, 106485 https://doi.org/10.1016/j.soildyn.2020.106485.

López-Austin, A., López-Luján, L., Sugiyama, S., 1991. The temple of Quetzalcoatl at Teotihuacan: its possible ideological significance. Anc. Mesoam. 2, 93–105. https://doi.org/10.1017/S0956536100000419.

Manning, J.G., Ludlow, F., Stine, A.R., Boss, W.R., Sigl, M., Marlon, J.R., 2017. Volcanic suppression of Nile summer flooding triggers revolt and constrains interstate conflict in ancient Egypt. Nat. Commun. 8, 900. https://doi.org/10.1038/s41467-017-00957-y.

Manzanilla, L., 2015. Cooperation and tensions in multiethnic corporate societies using teotihuacan, Central Mexico, as a case study. Proc. Natl. Acad. Sci. 112, 9210–9215. https://doi.org/10.1073/pnas.1419881112.

Manzanilla, L. 2005. Migrantes Epiclásicos en Teotihuacán. Propuesta metodológica para el análisis de migraciones del Clásico al Posclásico. In: Manzanilla (Ed), Reacomodos demográficos del Clásico al Posclásico en el centro de México, 261-273 pp. Universidad Nacional Autónoma de México, Instituto de Investigaciones Antropológicas. In Spanish.

Marco, S., 2008. Recognition of earthquake-related damage in archaeological sites: Examples from the Dead Sea fault zone. Tectonophysics 453, 148–156. https://doi.org/10.1016/j.tecto.2007.04.011.

Matos-Moctezuma, E., 2009. Teotihuacán. Fondo de Cultura Económica. Fideicomiso Historia de las Américas. Ciudad de México, 154 pp. ISBN: 9786071600820. (In Spanish).

Millon, R., 1966. Extensión y población de la ciudad de Teotihuacán. Un cálculo provisional. XI Mesa Redonda Teotihuacán. Sociedad Mexicana de Antropología, Ciudad de México in Spanish.

Millon, R., 1973. The Teotihuacan Map. Text. Urbanization at Teotihuacan, Mexico, pt. 1. University of Texas Press, Austin.

Millon, R., 1988. The last years of Teotihuacan dominance. In: Yoffee, N., Cowgill, G. (Eds.), The Collapse of Ancient States and Civilizations. The University of Arizona Press, Tucson.

Millon, R., Drewitt, B., Bennyhoff, J., 1965. The pyramid of the sun at Teotihuacán: 1959 investigations. Trans. Am. Philos. Soc. 55 (6), 1–93. https://doi.org/10.2307/1005892.

Miranda, T., Sousa, L.R., Gomes, A.T., Tinoco, J., Ferreira, C., 2018. Geomechanical characterization of volcanic rocks using empirical systems and data mining techniques. J. Rock Mech. Geotech. Eng. 10, 138–150. https://doi.org/10.1016/j.jrmge.2017.11.003.

Moragas-Segura, N., Sarabia-González, A. 2007. TEOTIHUACAN. Arqueoweb: Revista sobre Arqueología en Internet, Vol. 8, N°. 2, ISSN-e 1139-9201. In Spanish.

Moragas-Segura, N. 2013. Sociedades en colapso: la transición del Clásico al Epiclásico en Teotihuacán. Diálogo Andino, N° 41, 185-197. In Spanish.

Murakami, T., Boulanger, M.T., Glascock, M.D., 2018. Petrographic and XRF analyses of andesitic cut stone blocks at Teotihuacan, Mexico: implications for the organization of urban construction. Archaeol. Anthropol. Sci. https://doi.org/10.1007/s12520-018-0619-5.

Nichols, D.L., 2016. Teotihuacan. J. Archaeol. Res. 24 (1), 1–74. https://doi.org/10.1007/s10814-015-9085-0.

Nichols, D., 2020. City, State, and hinterlands. Teotihuacan and Central Mexico. In: Hirth, K.G., Carballo, D.M., Arroyo, B. (Eds.), Teotihuacan, the World beyond the

City. Dumbarton Oaks Research Library and Collection, Washington, D.C., pp. 227–275
Nikonov, A., 1988. On the methodology of archaeoseismic research into historical monuments. In: Marinos, G., Koukis, G. (Eds.), Engineering Geology of Ancient Works, Monuments and Historical Sites. Balkema, Roterdam, p. 1325.
Pérez-López, R., 2012. Ancient earthquakes hit the Quetzalcóatl Pyramid at Teotihuacán (México). Was it a stricken critical facility? Quat. Int. 279–280 (16), 375. https://doi.org/10.1016/j.quaint.2012.08.1156.
Pérez-López, R., Rodríguez-Pascua, M.A., Giner-Robles, J.L., Elez, J., Perucha, M.A., Silva, P.G., Roquero, E. 2019. Teotihuacan ancient culture depressed by a mega-earthquake associated to the seismic Guerrero gap recorded in Cacahumilpa Cave and EAEs (Mexico). 20th Congress of INQUA, online abstracts: https://app.oxfordabstracts.com/events/574/program-app/submission/89078.
Pérez-López, R., Rodríguez-Pascua, M.A., Garduño-Monroy, V.H., Oliveros, A., Giner-Robles, J.L., Silva, P.G., 2010. Probable Earthquake Archaeological Effects in the ancient pyramids of Quetzalcoatl and Sun in Teotihuacán (Central Mexico). Geophys. Res. Abstr. 12. EGU2010-2512.
Piña-Flores, J., Cárdenas-Soto, M., Sarabia-González, A., García-Jerez, A., Sierra-Álvarez, C.A., Sáenz-Castillo, M.A., Luzón, F., Sánchez-Sesma, F.J., 2020. Imaging the structure of the sun pyramid (Teotihuacán, Mexico) from passive seismic methods. Eng. Geol. 105969. https://doi.org/10.1016/j.enggeo.2020.105969.
Price, T.D., Spence, M.W., Longstaffe, F.J., 2020. The temple of Quetzalcoatl, Teotihuacan: new data on the origins of the sacrificial victims. Anc. Mesoam. 1–16 https://doi.org/10.1017/S095653611900035X.
Rattray, E.Ch. 1991. Fechamientos por Radiocarbono en Teotihuacan". Arqueología 6, 3-19, Revista INAH, 2ª época, México. In Spanish.
Reimer P.J., Austin, W.E.N., Bard, E., Bayliss, A., Blackwell, P. G., Ramsey, C. B., Butzin, M., Cheng, H., Edwards, R. L., Friedrich, M. l., Grootes, P. M., Guilderson, T. P., Hajdas, I., Heaton, T. J., Hogg, A. G., Hughen, K. A., Kromer, B., Manning, S. W., Muscheler, R., Palmer, J. G., Pearson, Ch., van der Plicht, J., Reimer, R. W., Richards, D. A., Scott, E. M., Southon, J. R., Turney, C. S. M., Wacker, L., Adolphi, F., Büntgen, U., Capano, M., Fahrni, S. M., Fogtmann-Schulz, A., Friedrich, R., Köhler, P., Kudsk, S., Miyake, F., Olsen, J., Reinig, F., Sakamoto, M., Sookdeo, A., Talamo, S., 2020. The IntCal20 Northern Hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon 62(4), 725-757. 10.1017/RDC.2020.41.
Rodríguez-Pascua, M.A., Benavente-Escobar, C., Rosell-Guevara, L., Grützner, C., Audin, L., Walker, R., García, B., Aguirre, E., 2020. Did earthquakes strike Machu Picchu? J. Seismol. 24, 883–895. https://doi.org/10.1007/s10950-019-09877-4.
Rodríguez-Pascua, M.A., Garduño-Monroy, V.H., Israde-Alcánta, I., Perucha, M.A., Pérez-López, R., Giner-Robles, J.L., Sánchez-Jiménez, N., 2021a, Evidencias paleosísmica y arqueosísmica de la simbología Posclásico Tardía P'urepecha en Michoacán (México). ¿Primeras señalizaciones sísmicas de la historia?: Boletín de la Sociedad Geológica Mexicana, 73 (2), A161220. 10.18268/BSGM2021v73n2a161220.
Rodríguez-Pascua, M.A., Silva, P.G., Giner-Robles, J.L., Perucha, M.A., Roquero, E., Bardají., T., Elez, J., Pérez-López, R. 2022. Earthquake Archaeological Effects (EAEs) for Identification of seismic damage and intensity assessments in the cultural heritage. In: Handbook of Cultural Heritage Analysis, D'Amico, Sebastiano, Venuti, Valentina (Eds.), Springer Nature Switzerland AG. 10.1007/978-3-030-60016-7_61.
Rodríguez-Pascua, M.A., Pérez-López, R., Silva, P.G., Giner-Robles, J.L., Garduño-Monroy, V.H., Reicherter, K., 2011. A comprehensive classification of Earthquake Archaeological Effects (EAE) for Archaeoseismology. Quat. Int. 242, 20–30.
Rodríguez-Pascua, M.A., Pérez-López, R., Garduño-Monroy, V.H., Perucha, M.A., Israde-Alcántara, I., 2017. Estimation of the epicentral area of the 1912 Acambay earthquake (M 6.9, Mexico) determined from the earthquake archaeological effects (EAE) and the ESI07 macroseismic scale. Quat. Int. 451 (7), 74–86. https://doi.org/10.1016/j.quaint.2017.06.045.
Sarro, P.J., 1991. The role of architectural sculpture in ritual space at Teotihuacan, Mexico. Anc. Mesoam. 2, 249–262. https://doi.org/10.1017/S0956536100000572.
Sawires, R., Santoyo, M.A., Peláez, J.A., Corona-Fernández, R.D., 2019. An updated and unified earthquake catalog from 1787 to 2018 for seismic hazard assessment studies in Mexico. Sci. Data 6, 241. https://doi.org/10.1038/s41597-019-0234-z.
Schellart, W.P., Rawlinson, N., 2013. Global correlations between maximum magnitudes of subduction zone interface thrust earthquakes and physical parameters of subduction zones. Phys. Earth Planet. In. 225, 41–67. https://doi.org/10.1016/j.pepi.2013.10.001.
Siebe, C., 2000. Age and archaeological implications of Xitle volcano, southwestern Basin of Mexico-City. J. Volcanol. Geoth. Res. 104, 45–64. https://doi.org/10.1016/S0377-0273(00)00199-2.
Siebe, C., Rodríguez-Lara, V., Schaaf, P., Abrams, M., 2004. Radiocarbon ages of Holocene Pelado, Guespalapa, and Chichinautzin scoria cones, south of Mexico City: implications for archaeology and future hazards. Bull. Volcanol. 66, 203–225. https://doi.org/10.1007/s00445-003-0304-z.
Silva, P.G., Borja, F., Zazo, C., Goy, J.L., Bardaji, T., De Luque, L., Lario, J., Dabrio, C.J., 2005. Archaeoseismic record at the ancient Roman City of Baelo Claudia (Cádiz, south Spain). Tectonophysics 408 (1–4), 129–146.
Silva, P.G., Reicherter, K., Grutzner, C.H., Bardaji, T., Lario, J., Goy, J.L., Zazo, C., Becker-Heidmann, P., 2009. Surface and subsurface palaeoseismic records at the ancient Roman city of Baelo Claudia and the Bolonia Bay area, Cádiz (south Spain). Geol. Soc. Lond. Spec. Publ. 316, 93–121.
Sintubin, M., Stewart, I.S., Niemi, T.M., Altunel, E. (Eds.), 2010. Ancient Earthquakes: Geological Society of America Special Paper 471. GSA, Boulder, Colorado (USA), p. 279.
Stiros, S., Jones, R.E. 1996. Archaeoseismology. Institute of Geology and Mineral Exploration. Fitch Laboratory Occasional Paper. In: Stiros S., and Jones, R.E. (Eds.) Atenas, 268 p.
Stiros, S.C., 1996. Identification of earthquakes from archaeological data: methodology, criteria and Limitations. Fitch Laboratory Occasional Paper 7. In: Stiros, S., Jones, R. (Eds.), Archaeoseismology. British School at Athens, 129-152.
Suarez, G., Albini, P., 2009. Evidence for Great Tsunamigenic Earthquakes (M 8.6) along the Mexican Subduction Zone. Short Note. Bull. Seismol. Soc. Am. 99 (2A), 892–896. https://doi.org/10.1785/0120080201.
Suárez, G., García-Acosta, V., 2021. The first written accounts of pre-hispanic Earthquakes in the Americas. Seismol. Res. Lett. XX 1–9. https://doi.org/10.1785/0220210161.
Suárez, G., Ruiz-Barón, D., Chico-Hernández, C., Zúñiga, F.R., 2020. Catalog of preinstrumental Earthquakes in Central Mexico: epicentral and magnitude estimations based on Macroseismic Data. Bull. Seismol. Soc. Am. XX 1–16. https://doi.org/10.1785/0120200127.
Sugiyama, S., 1989. Burials dedicated to the Old Temple of Quetzalcoatl at Teotihuacan, Mexico. Am. Antiq. 54 (1), 85–106.
Sugiyama, S., 1993. Worldview Materialized in Teotihuacan, Mexico. Latin Am. Antiq. 4 (2), 103–129. https://doi.org/10.2307/971798.
Sugiyama, S., 2005. Human Sacrifice, Militarism, and Rulership: Materialization of State Ideology at the Feathered Serpent Pyramid, Teotihuacan (New Studies in Archaeology, pp. I-Vi). Cambridge University Press, Cambridge.
Sugiyama, S., Cabrera-Castro, R., 2007. The moon pyramid project and the Teotihuacan state polity. Anc. Mesoam. 18, 109–125. https://doi.org/10.1017/S0956536107000053.
Sugiyama, N., Sugiyama, S., Sarabia, A., 2013. Inside the Sun pyramid at Teotihuacan, Mexico: 2008–2011 excavations and preliminary results. Lat. Am. Antiq. 24 (4), 403–432. https://doi.org/10.7183/1045-6635.24.4.403.
Tuğrul, A., Gürpinar, O., 1997. A proposed weathering classification for basalts and their engineering properties (Turkey). Bull. Int. Assoc. Eng. Geol. 55, 139–149.
Viles, H., Messenzehl, K., Mayaud, J., Coombes, M., Bourke, M., 2018. Stress histories control rock-breakdown trajectories in arid environments. Geology 46 (5), 419–422. https://doi.org/10.1130/G39637.1.