





# Landslide impact on the archaeological site of Mitla, Oaxaca

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## Abstract

Some large landslide deposits are recognized within and around the Mitla archaeological site, which is located in a very seismically active region cut by the Tehuacan-Oaxaca fault system. Previous studies have shown that this fault system has produced coseismic ruptures and associated earthquakes in the past. Our work on the Mitla landslide deposits clearly demonstrates that their morphology and nature are typical of dry-rock avalanches. Thus, collapses of rock already weakened by alteration and/or weathering, and unstably mobilized by intense rainfall, are discarded as possible triggers of the avalanche events. We instead propose that the landslides were triggered by earthquake activity. Moreover, our data indicate that part of the original Mitla settlement lies buried under a large rock-avalanche deposit produced sometime during the post-Classic period (900–1520 AD). At that time, the city of Mitla was inhabited by over 10,000 people as estimated from archaeological reconstructions. This devastating landslide almost entirely obliterated Mitla, which at the time of the Spanish arrival still existed as a city, but much reduced in area and populations.

## KEYWORDS

archaeoseismology, earthquake, landslide, Mesoamerican, Mitla

## 1 | INTRODUCTION

### 1.1 | Landslides

Landslides are downslope gravitational processes that occur along a surface or rupture zone through which intense shear strain occurs (Hung, Leroueil, & Picarelli, 2014). The transported mass abruptly modifies the morphology of the surrounding terrain, commonly blocking

perennial rivers with debris that led to the formation of natural dams (Costa & Shuster, 1988). Some authors also concluded that landslides might affect the ecosystems and the human settlements nearby (Bhattacharyya et al., 2015). A good example of prehistoric landslides affecting human settlements is given by the Mitla archaeological site in the state of Oaxaca. These landslides are situated along a NW–SE strike-slip fault that cuts the Calavera range made of a thick sequence of Miocene ignimbrites. Strikingly, the steep front of one of these

Dr. Víctor Garduño Monroy is deceased.

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landslides stands at less than 1 km from the main entrance to the Mitla ceremonial center. The landslide morphology and close proximity to Mitla lead us to ask if this event perhaps occurred during the occupation of Mitla by the Zapotec Empire from 900 to 1521 AD.

Although the Mitla archaeological site stands only a few hundred meters from the landslide front, surprisingly, this deposit has not been previously described in the geological literature (Ferrusquía-Villafranca, 1990; Ferrusquía-Villafranca, Wilson, Denison, McDowell, & Solorio-Munguía, 1974; Iriondo, Kunk, Winick, & C.R.M., 2004) nor in the archaeological studies (Robles-García, 2016). In this study, we present the results of the morphological and geological characterization of the landslide deposits and their spatial and temporal distribution with respect to the pre-Hispanic ceremonial center of Mitla. In particular, we focused on the landslide depositional chronology, the possible triggers, and its' possible repercussions for the pre-Columbian population of Mitla, the second most important human settlement of the Oaxaca valleys. By combining the geological and shallow geophysical techniques (e.g., electrical tomography), we provide new evidence that suggests that the ceremonial center could have been directly affected by the landslide.

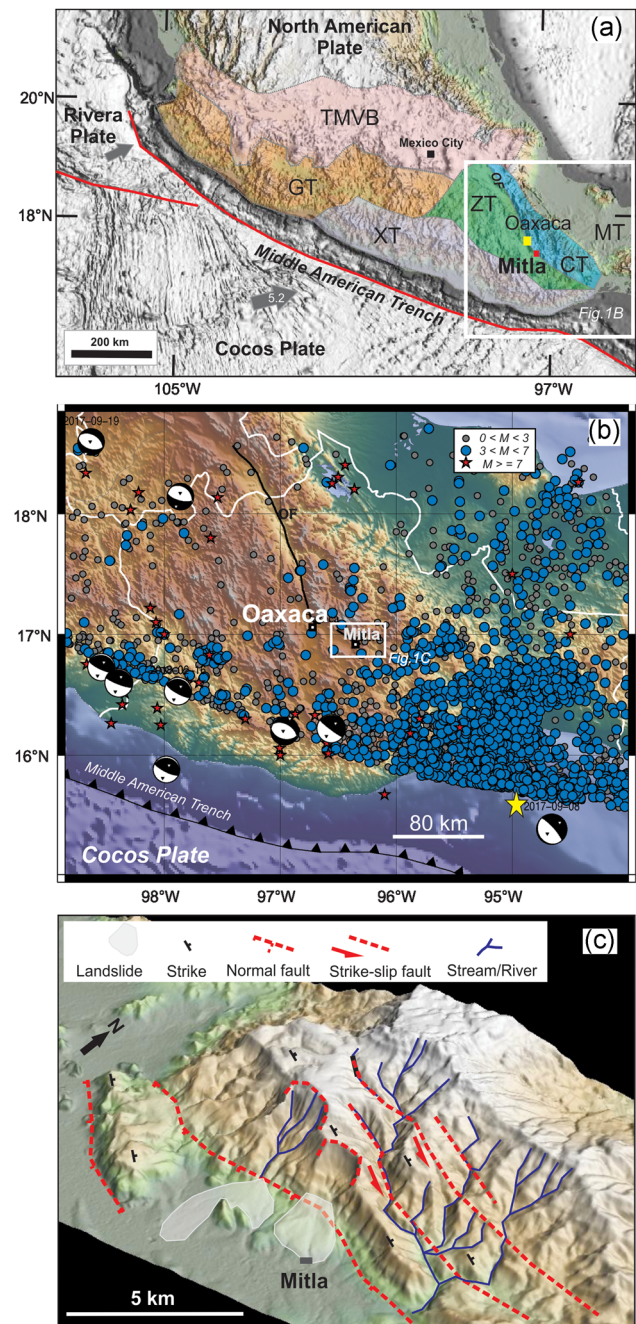
## 1.2 | Tectonic setting of Oaxaca

The state of Oaxaca is one of the most active seismic zones in southern Mexico because of the subduction of the Cocos Plate beneath the North American Plate along the Middle American Trench (Pardo & Suárez, 1995) (Figure 1a). This tectonic environment produces both earthquakes along the subduction zone and intraplate shallow earthquakes (Figure 1b). The earthquake of September 7, 2017, in Oaxaca, and the shallow Xalapa earthquake that took place in 1920 ( $M_s$  6.4, Córdoba-Montiel, Krishna Singh, Iglesias, Pérez-Campos, & Sieron, 2018) are examples of these two types of seismic activity. Mitla is located within an area that is subjected to both subduction and intraplate earthquakes, the latter is associated with movements along the boundary of two tectonic terranes exposed in the Central and Tehuacán Valleys. In fact, the Central Valleys of Oaxaca are part of the Oaxaca fault system that forms the tectonic boundary between the Zapoteco and Cuicateco terranes (Figure 1c).

## 1.3 | The Mitla archaeological site

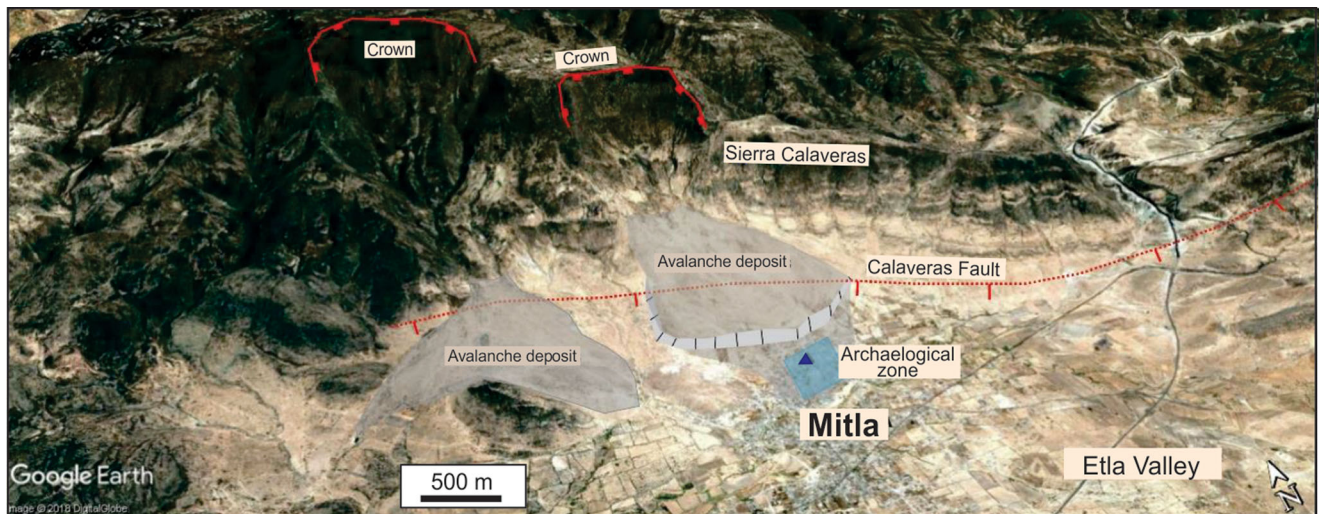
Mitla is located south of the City of Oaxaca, capital of the State of the same name, along the NW-SE Etlá Valley (Figure 2). Mitla's climate is dry temperate (Köppen-Geiger Bsk), with an average rainfall of 623 mm and an average temperature of 17.4°C. The name Mitla or Mictlán is of Náhuatl origin and means "Place of the Dead" or "Underworld." In Zapotec, it is called *Lyobaa* which means "Place of Burials"; in the Mexica language, it remained Mitlán, "Place of the Dead," or "place of many corpses," and was Hispanicized to Mitla (Corner, 1899). Mitla's zenith occurred between 950 and 1521 AD, when it covered an estimated area of over 7,000 km<sup>2</sup>, with a population of approximately 10,000 inhabitants. Among Mitla's specific attractions are buildings

decorated with elaborate mosaic fretwork (*grecales*) showing variations of the same geometric design, and cross-shaped tombs that have been found beneath the palaces, in which important people and priests were presumably buried. The archaeological complex includes several



**FIGURE 1** (a) Tectonic sketch of southern Mexico showing the tectonic terrains described by Campa and Coney (1983) and the tectonic plate configuration. (b) Seismicity reported (1917–1919) with depths between 0 and 20 km deep by the Servicio Sismológico Nacional, greater earthquake (stars) and focal mechanisms from IRIS consortium. (c) Structural scheme of the Mitla area and the location of the landslides described in this study modified from Garduño-Monroy et al. (2019). CT, Cuicateco Terrane; GT, Guerrero Terrane; MT, Maya Terrane; TMVB, Trans-Mexican Volcanic Belt; XT, Xolapa Terrane; ZT, Zapoteco Terrane [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

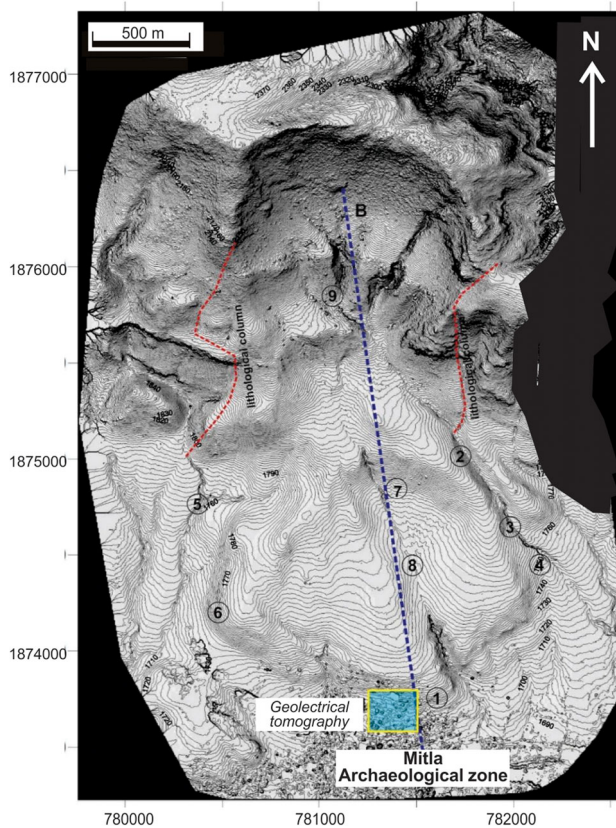




**FIGURE 2** Panoramic view showing the Sierra La Calavera, Calaveras Fault, Etna Valley, and the two studied landslides around the Mitla archaeological zone and city. The blue polygon indicates the possible extension of the pre-Columbian settlement. Satellite image from Google Earth™ [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

structures, two of these are now covered by Christian buildings, the most important of which (the San Pablo church) was built in 1590. This imposing church was erected in one of the pre-Columbian courts of

Mitla using stones from the pre-Hispanic temples themselves. The basic architectural form of the few structures corresponds to earthquake-resistant techniques. According to Robles-García (2016), Mitla had already begun to decline before the arrival of the Spaniards in the 16th century (Robles-García, 2016), although the causes of such decline have not been clarified yet.



**FIGURE 3** Digital Elevation Model (DEM) of the studied area including the archaeological site and the numbers of selected stratigraphic sections. The blue line represents the geological section shown in Figure 6. The blue box is the surveyed area during the geoelectrical tomography [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

## 2 | METHODOLOGY

This research comprised six components (a) a review of previous archaeological and geoscientific studies about Mitla (ancillary data); (b) the construction of a geological-geomorphological map employing a 50 cm-resolution terrain model obtained with an unmanned aerial vehicle survey (Figure 3); (c) the definition of the lithologic features and the design of the fieldwork to characterize the petrophysical properties of the avalanche, to verify the geological and stratigraphic data, and to plan the geophysical, morphostructural, structural, and geomechanical studies; (d) Field reconnaissance across the most representative sites with an underground model reconstructed through interpolations of the identified stratigraphic columns; (e) the conduct of seismic and electrical tomographic studies, and (f) the simulation of the slope behavior during an earthquake and verification of safety factors.

## 3 | RESULTS

### 3.1 | Geomorphology

This region of the Etna Valley overlies Precambrian rocks of the Zapoteco terrane covered by Mesozoic carbonates, and rhyolitic ignimbrites that constitute the Sierra La Calavera (Ferrusquía-Villafranca, 1990; Figure 1c). These rocks form aligned sierras and valleys, where the N-S drainage system is occasionally modified by NW-SE structures

(Figure 1c). The geomorphology of the Mitla area comprises three main morphological elements:

(a) To the north, the prominent NW–SE-oriented Sierra La Calavera with peaks of up to 2300 m with parallel and dendritic drainage, formed by up to 500 m-thick pink to white rhyolitic ignimbrite presenting several layers with varying degrees of welding (Figure 4). These ignimbrites are of Miocene age (Ferrusquía-Villafranca, 1990; Iriondo et al., 2004); (b) Hills running parallel to the sierra formed by rock-avalanche deposits; and (c) The valley with elevations of ca. 1200 m with fluvial and lacustrine deposits of Pleistocene age (Ferrusquía-Villafranca, 1990). Strikingly, the Sierra La Calavera exhibits two concave areas or scars associated with landslide deposits in the lower part of the valley that have not been described before.

A digital elevation model (DEM) of the area shows two scars at Sierra La Calavera that are open towards the south and have associated rock avalanche deposits (Figure 3). The Mitla scar has a considerable crown with a maximum diameter of 1,350 m, and a vertical slope relief of 390 m. The landslide extends more than 2,500 m from the base of the crown to the deposit front. The second crown, located NNW of Mitla, is less regular, has a maximum diameter of 1,700 m and a vertical slope relief of 390 m. This landslide extends more than 4,000 m from the basis of the crown to the deposit front (Figures 3 and 4). Both crowns are located within the footwall of the normal La Calavera fault that formed the Etna Valley.

### 3.2 | Local geology

The stratigraphic succession around Mitla is mainly composed of the basement rocks and the rhyolitic ignimbrites that form the Sierra La Calavera (Figure 4). On top of this stratigraphic succession, we have

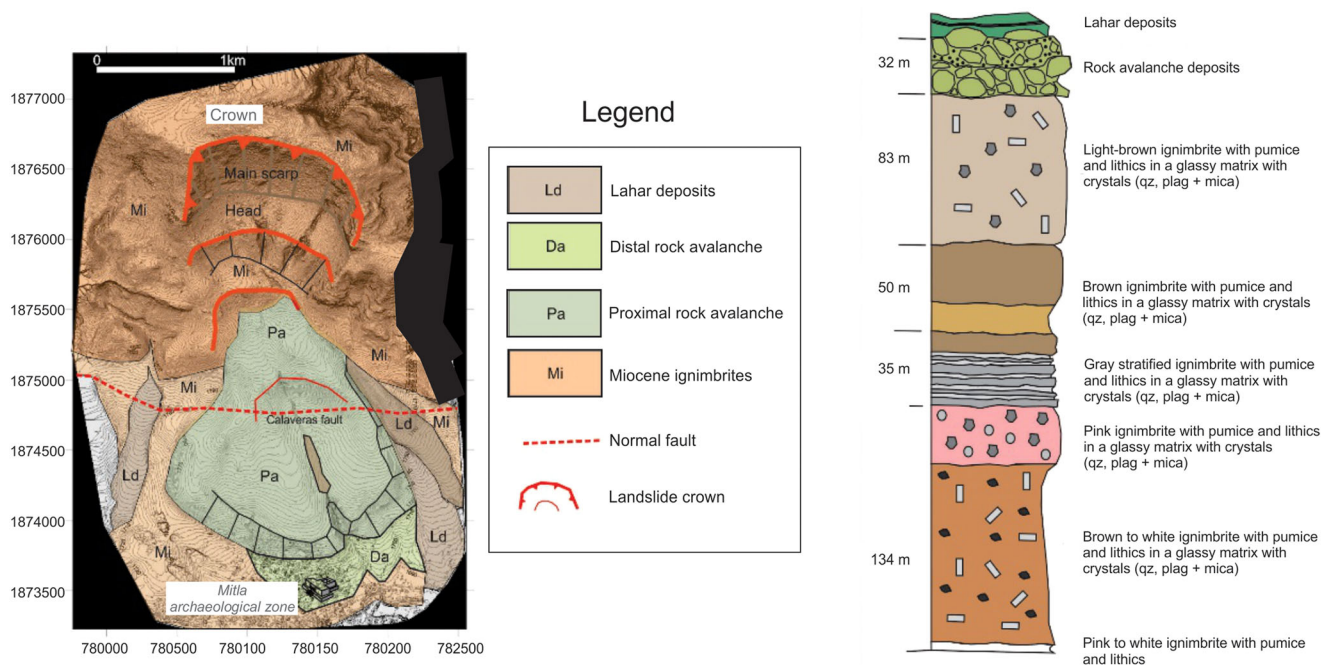
faulted fluvio-lacustrine deposits comprising layers of conglomerates, sands, and clays that contain large Pleistocene vertebrates (Ferrusquía-Villafranca, 1990 and Ferrusquía-Villafranca et al., 1974). All these rocks are transected by NNW–SSE left-lateral strike-slip faults. The main fault here called the Calavera, is one of the regional faults that bound the Zapoteco and Cuicateco terranes.

The stratigraphy of the area is dominated by the rhyolitic ignimbrites that are very well exposed on the hanging wall and scars of the Calavera fault (Figure 4). This ignimbrite was first described by Williams and Heizer (1965) during the reconnaissance studies at the Mitla Fortress. These ignimbrites are made of at least two thick successions; the lower one corresponds to the hanging wall of the normal La Calavera fault exposed at La Fortaleza and Mitla; the upper succession corresponds to the Sierra La Calavera and is composed of at least four thick units, some of which are welded. All units contain quartz, plagioclase, and mica phenocrysts set in a glassy matrix. These ignimbrites were dated between  $14.4 \pm 0.4$  and  $15.48 \pm 0.2$  My (Miocene) with the  $^{40}\text{Ar}/^{39}\text{Ar}$  method (Iriondo et al., 2004). At the base of the hanging wall and on top of these ignimbrites rest two rock-avalanche deposits composed mainly of shattered rhyolitic ignimbrites, one of them at Mitla that is the focus of this study. Debris flows and hyper-concentrated flow deposits cover and cut the rock-avalanche deposits and ignimbrites along main ravines.

## 4 | THE MITLA ROCK AVALANCHE

### 4.1 | Description of the deposit

The mapped rock-avalanche deposit can be divided into four large parts. This deposit consists of ignimbrite blocks with jigsaw-puzzle



**FIGURE 4** Geological map of the Mitla area and composite lithological column of the mapped deposits [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



structures set in an intraclast matrix. These blocks range in size from gravel to megablocks ( $\geq 5$  m in diameter) with angular to subrounded forms (Figure 5a). Towards the top of the deposit there are small reverse faults that appear like little ramps and thrusts. Close to the archaeological zone, the deposit consists of two parts:

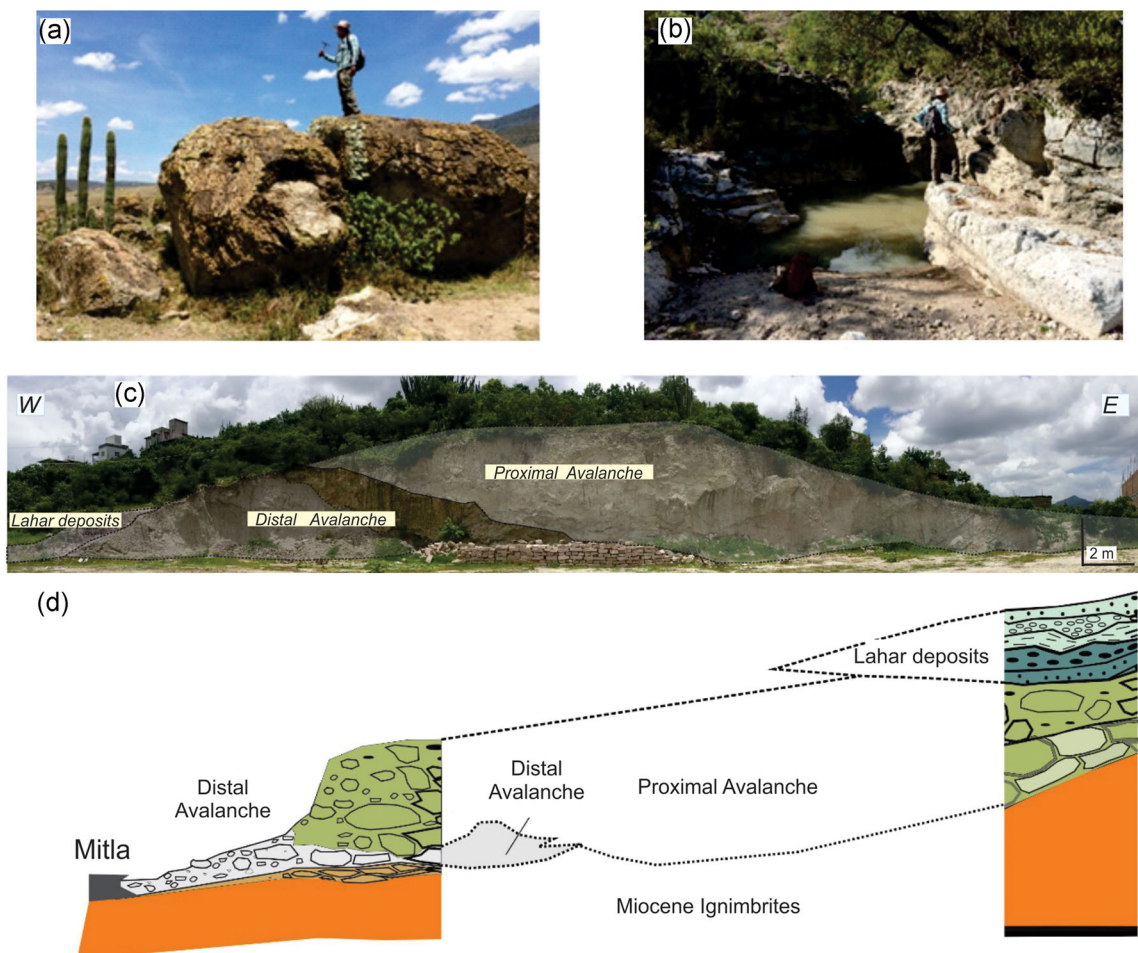
(a) The bottom part is clast-supported (block-facies) comprising ignimbrite blocks with an intraclast sandy matrix of the same composition (Figure 5b,c). The blocks are subangular and sometimes subrounded not exceeding 1 m in diameter. This block facies occurs in several parts along the rock-avalanche front and are called distal avalanches; (b) The upper part is made of dispersed mega-blocks ( $\geq 5$  m in diameter) set in a sandy to gravel-sized matrix (here called proximal avalanche). These mega-blocks appear at the surface of the deposit and are characteristic of this level.

Overlying the rock-avalanche deposit are deposits that vary from debris flows to hyper-concentrated flows, comprising the same ignimbrite blocks embedded in a silty-clayey matrix. Above these deposits, we found a layer of mudflow deposits that contain ceramic shards (Figure 5d).

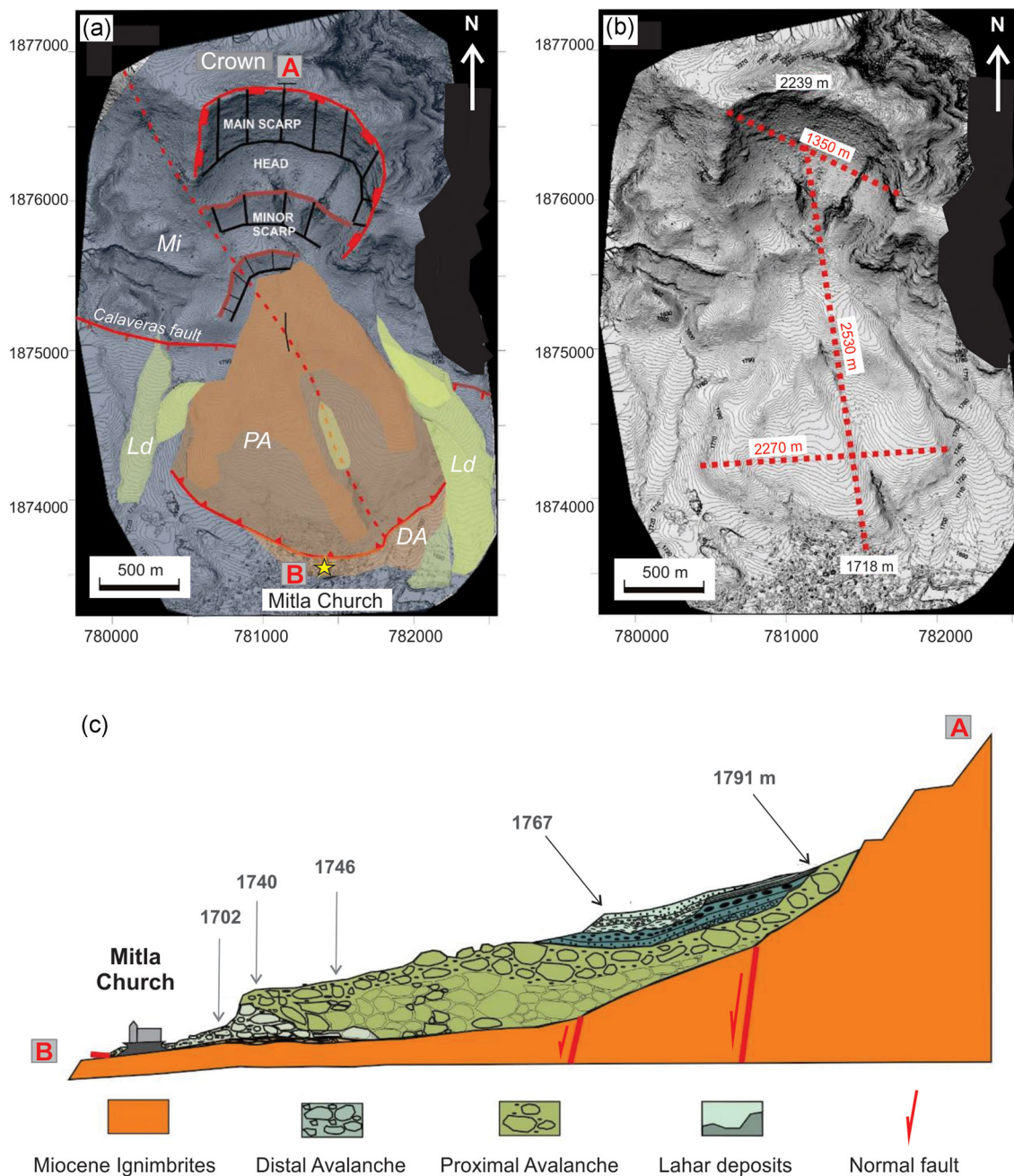
We calculated the area and volume of the rock avalanches using ArcMap 10.2 software and the DEM (Figure 6). The rock avalanches cover an area of 4.19 km<sup>2</sup> and possess an average thickness of 0.06 km. Therefore, we estimate a minimum total volume of approximately 0.2 km<sup>3</sup> for the two deposits combined with about 0.1 km<sup>3</sup> for each.

## 4.2 | Coefficient of friction ( $H/L$ )

The vertical drop versus the maximum runout distance traveled by a landslide is known as the apparent friction coefficient ( $H/L$ ) that was introduced by Hsü (1975). The coefficient of friction was then used to describe debris avalanches in volcanic terrains (Ui, 1983), and then by Francis (1993) for various types of landslides (Legros, 2002; Morelli et al., 2010, 2016; Salvatici, Di Roberto et al., 2016; Salvatici, Morelli, Di Traglia, & Di Roberto, 2016). For small-size landslides, the apparent coefficient of friction is about 0.6 while for larger size landslides, this value typically is about 0.2. For the case of the Mitla landslide, we obtained a maximum drop of 640 m with a maximum runout of 1,633 m



**FIGURE 5** Different aspects of the Mitla rock-avalanche deposit. (a) A block exposed on the surface of the rock avalanche that is approximately 6 m in diameter. (b) Reverse faults in the ignimbrite rocks exposed on the hanging wall of the scar, (c) Quarry exposing two main beds of the rock-avalanche deposit. (d) Lithology exposed at the rock-avalanche front. The tip part of the distal avalanche covers part of the archaeological site with at least 2 m of debris [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



**FIGURE 6** The simplified geological map (a), and DEM (b) of the studied area, and (c) an exaggerated geological cross-section A-B from the scar to the Mitla archaeological site (dotted red line). The numbers are the elevations in meters above sea level in stratigraphic sections constructed during fieldwork. DA, distal avalanche; DEM, digital elevation model; Ld, Lahar deposits; Mi, Miocene Ignimbrites; PA, proximal avalanche [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

that yielded an  $H/L = 0.39$  (Figure 7). This value in the chart of Figure 7 correlates with dry debris avalanches of nonvolcanic origin (Dade & Huppert, 1994). The Mitla debris-avalanche deposit comprises shattered blocks supported by a coarse ash matrix with no other associated pyroclastic deposits and with no evidence of transport by water (e.g., voids, rounded blocks). Therefore, it is plausible that the triggering mechanism for the landslide could have been an earthquake that promoted the downhill remobilization of the rocks.

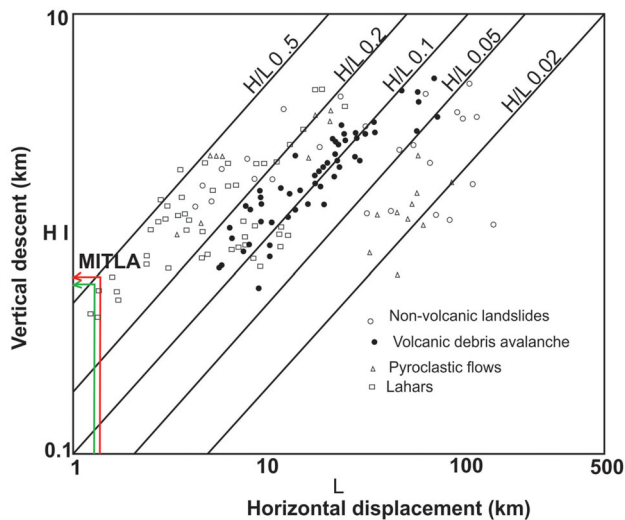
Hsü (1975) introduced an indicator regarding the mobility of landslides called excessive travel distance. This parameter ( $Le$ ) corresponds

to the horizontal distance traveled in excess by the event (i.e., above that expected) for a dry rigid mass sliding down on a slope with a normal coefficient friction of  $\tan 32$ .

$$Le = L - (H/0.62)$$

By substituting Mitla's rock-avalanche values of  $H$  and  $L$  in this formula, we obtained an excess travel distance of 600 m. This value is small in comparison with those calculated for rock avalanches that involve water among the triggering factors.





**FIGURE 7** Distance of travel versus drop height of volcanic and nonvolcanic rock avalanches (modified after Dade & Huppert, 1994). The Mitla's landslides have values of near 0.5. The red arrow corresponds to the Mitla rock avalanche and the green arrow to the rock avalanche located NW of Mitla [Color figure can be viewed at [wileyonlinelibrary.com](https://onlinelibrary.wiley.com)]

With water involved, this difference ( $L_e$ ) can be up to four times higher.

## 5 | SLOPE CHARACTERIZATION

### 5.1 | Geoelectrical tomography

Geoelectrical methods are widely used to characterize and monitor landslides (Pazzi, Morelli, & Fanti, 2019). The aim of geoelectrical mapping is to determine the distribution of resistivity in the subsoil via the passing of electrical current from the surface, thus permitting the estimation of subsoil resistivity. Resistivity results reflect geological parameters including the subsoil's mineral content, fluid saturation and rock porosity (Dahlin, 2001; Pazzi, Ceccatelli, Gracchi, Masi, & Fanti, 2018). Three 2D SUPERSTING tomographies with an inter-electrode distance of 4 m were taken to measure the geometry of the landslide (Figure 8). We obtained resolutions of 2 m vertically, and 4 m horizontally. Lines 1 and 2 are 108 m long and NW–SE oriented. Line 3 is 156 m long and NE–SW oriented. The results reveal a rock-avalanche body with low resistivities (11–17  $\Omega\text{m}$  and shown by blue color), and in the southern part of the profiles, below 4–5 m from the surface, a body of intermediate resistivity (22  $\Omega\text{m}$  with green and yellow colors), which has been interpreted as “in situ” ignimbrite, or possible remains of anthropogenic structures built originally in Mitla with ignimbrites. Ignimbrites typically are dense rocks with lower permeability or porosity than rock avalanches, which are made of loose materials and, therefore, have high porosity. Because our study was conducted in the rainy season, the pores in the rock avalanches were more saturated with fluids than in the ignimbrites, increasing their conductivity and decreasing the resistivity. Conversely,

ignimbrites have fewer and very small pores, which is why their conductivity was lower than that of the avalanche, consequently resulting in their higher resistivity. Other passive seismic studies were conducted in the area and are described in Garduño-Monroy et al. (2019).

### 5.2 | Geoslope modeling

In characterizing the conditions that can trigger slope movement, it is necessary to understand and quantify the main forces involved, namely shear strength and shear stress. To perform such slope-stability analysis, for this study we used the GeoSlope computer program (GEO-SLOPE International Ltd, 2008a), in particular its software package SLOPE/W. In assessing if the slope will move or not, GeoSlope calculates an indicator called “safety factor” (or sometimes, but less commonly, “security factor”). This factor is an expression of the relation between the forces resisting movement (that must be sufficiently strong to prevent slope movement) and the gravitational forces (that would cause the slope to fail). If the safety-factor value is equal to 1, the slope is considered at the limit of equilibrium conditions. Therefore, values of 1 or higher means that the slope is stable, and values lower than 1 means that the slope is unstable (Duncan, Wright, & Brandon, 2014). We calculated the safety factor in a distributed way over the entire investigated section (yellow line in Figure 9 inset). The results show that the upper parts of the slope, from 350 to 1,300 m, and between 450 and 650 m, the safety factor is lower than 1 (in red or orange in Figure 9 profile), which means it is unstable. This portion of the slope is near the crown of the large break caused by the La Calavera fault. The profile also indicates that farther downslope the safety factor increases (in green or blue) to values higher than 1, indicating that this portion of the slope is stable. These results allowed us to establish the boundary of the slope and to detect where the movement was resisted (Fidolini, Pazzi, Frodella, Morelli, & Fanti, 2015).

### 5.3 | Application of quake/W

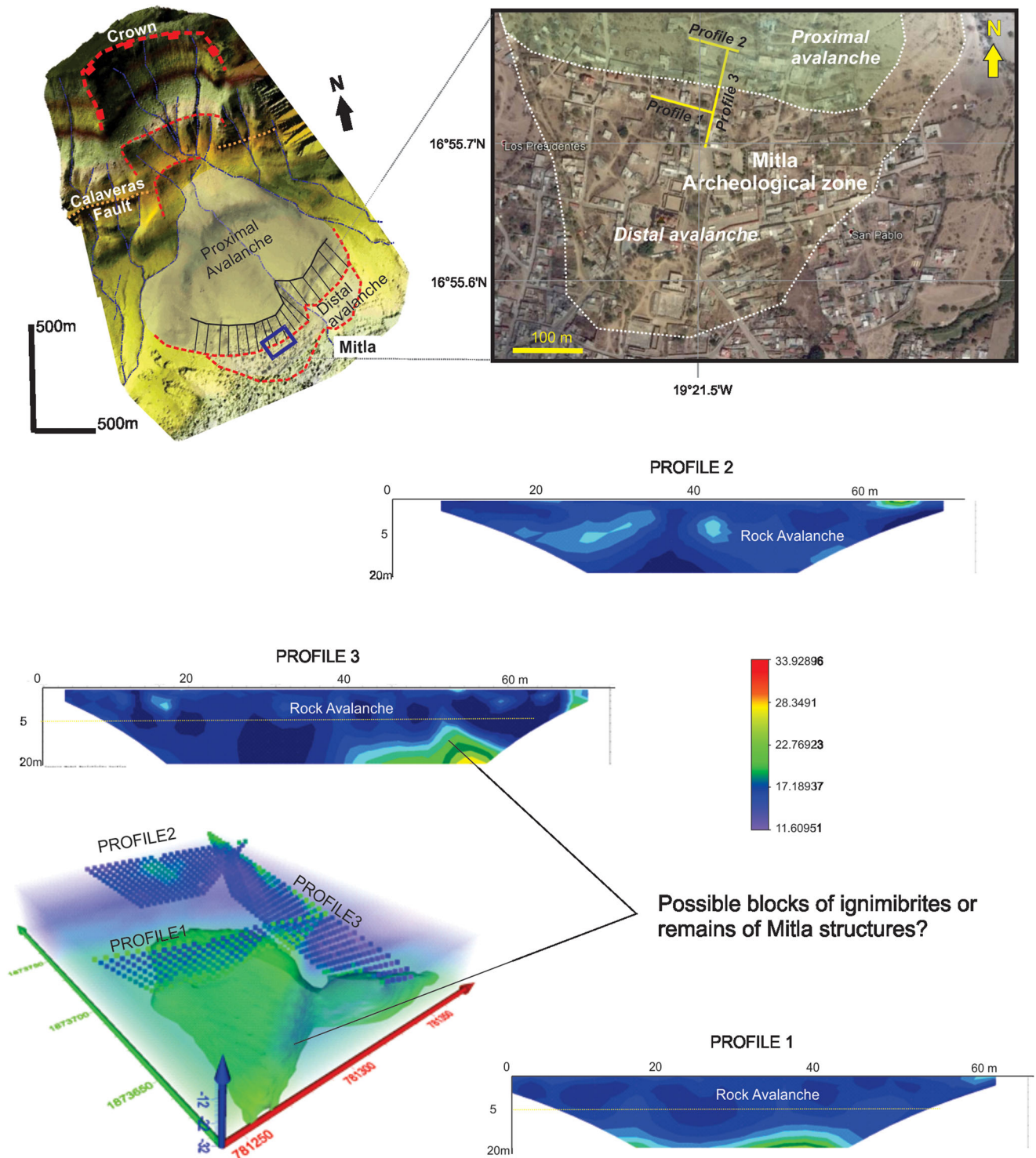
Slope-stability analysis can be studied both under static (see Section 6.2) and/or dynamic conditions (GEO-SLOPE International Ltd, 2008b). The analysis for dynamic slope behavior is performed when the landslide triggering mechanism is an earthquake, and can be carried out by means of a different GeoSlope software package, called Quake/W (Garevski, Zugic, & Sesov, 2013). The input data are the slope-boundary conditions and an accelerogram of the earthquake (Figure 10) that can trigger the avalanche/slope failure. Because seismic data do not exist for the earthquake in the Mitla case study, we used—as an analog—the data of the 1978 Oaxaca earthquake (Magnitude 7.8 Mw) provided by the Instituto de Ingeniería of UNAM (Unidad de Instrumentación Sísmica) (Table 1). With this input, we then calculated the dynamic slope behavior for the Mitla landslide. It is important to note that the Quake/W software creates a model for each time-lapse, in this case, every 0.10 s up to 14.95 s. The results obtained clearly indicate that an earthquake of this magnitude (7.8 Mw) can produce a landslide ( $\geq 0.55 \text{ km}^3$ ) that is about the same size as the one at Mitla.

## 6 | DISCUSSION

### 6.1 | Landslide generation

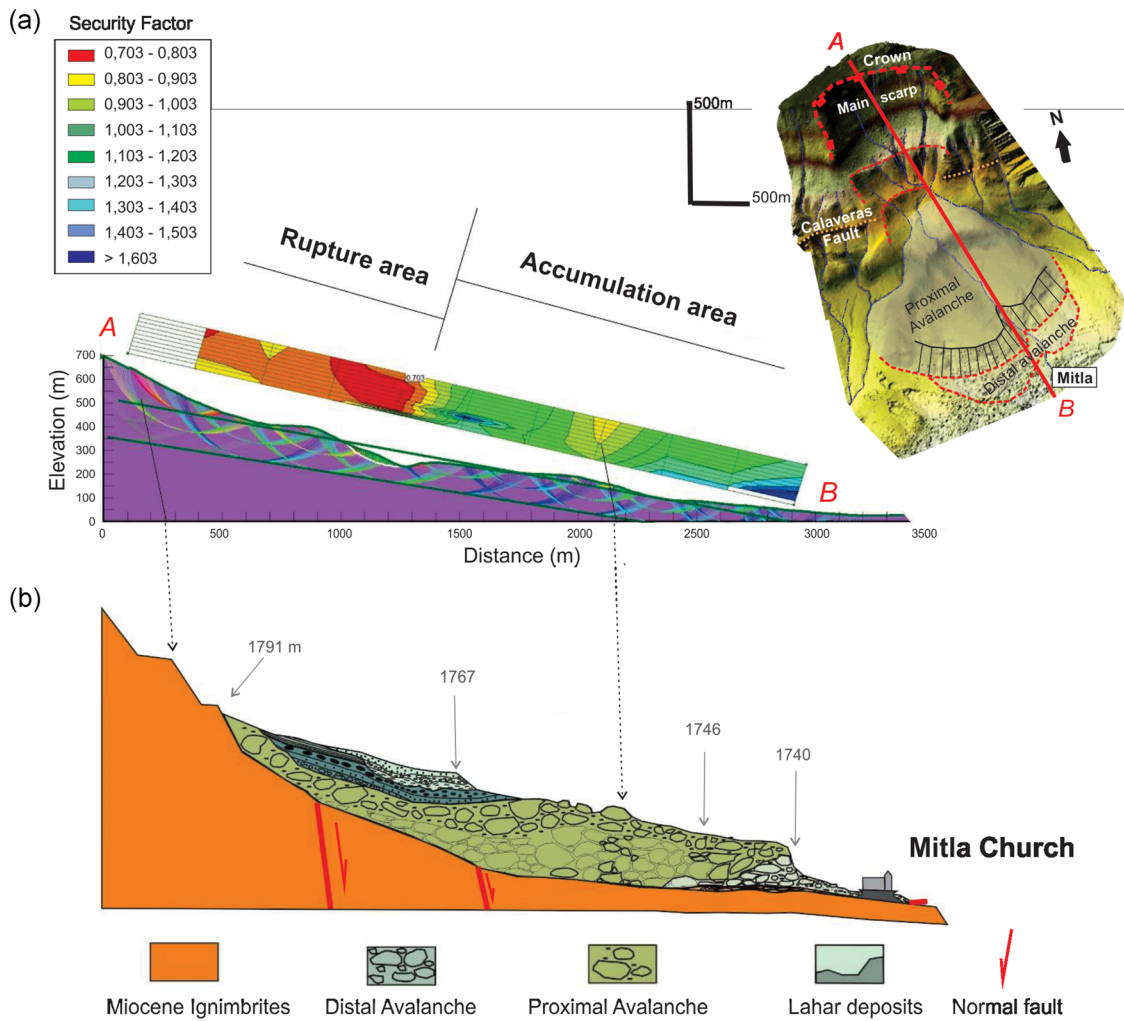
Crozier (1992) proposed six criteria to link landslides to a seismic origin in New Zealand that are given below: (a) The occurrence of

modern seismic activity in the study region that has triggered landslides. (b) The coincidence of landslide distribution with an active fault or seismic zone. (c) A high safety factor of slope stability, indicating the impossibility of its failure without additional (i.e., seismic) loading, (d) The large size of the landslide in question. (e) The presence of liquefaction features associated with landslides. (f) Landslides distribution



**FIGURE 8** Results of the geoelectrical tomography study performed for the rock-avalanche front and the archaeological zone. Note the presence of a body with intermediate resistivity (12) related to possible archaeological remains (green). The blue areas correspond to the deposits of the distal rock avalanche with thicknesses from 1 to 2.20 m [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

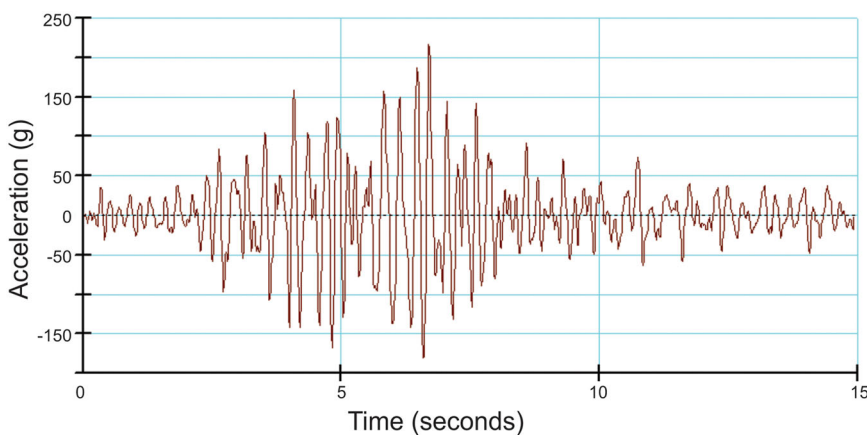




**FIGURE 9** Results obtained with the static stability analysis module of GeoSlope model along a longitudinal section located in the center of the landslide (as highlighted by the yellow line on the 3D model). The variation of the static safety factor (stable area with a factor higher than 1 in green and blue and unstable area with a factor lower than 1 in yellow and red) is shown from the output model (a) in correlation with the reconstruction of the material distribution inside the landslide mass (b) [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

that cannot be described solely on the basis of geological and geomorphic conditions. In a recent study of landslides in Asia, Strom and Abdrakmatov (2018) considered that with the exception of criteria 3 and 4 of Crozier (1992), most of the other criteria appeared to be met

in their compilation, as we also do observe for the Mitla landslides in Oaxaca. Taking into account the geomorphology of the Mitla rock avalanche (e.g., steep front) and the physical structure of the deposit (composed of shattered blocks with an intraclast matrix produced by



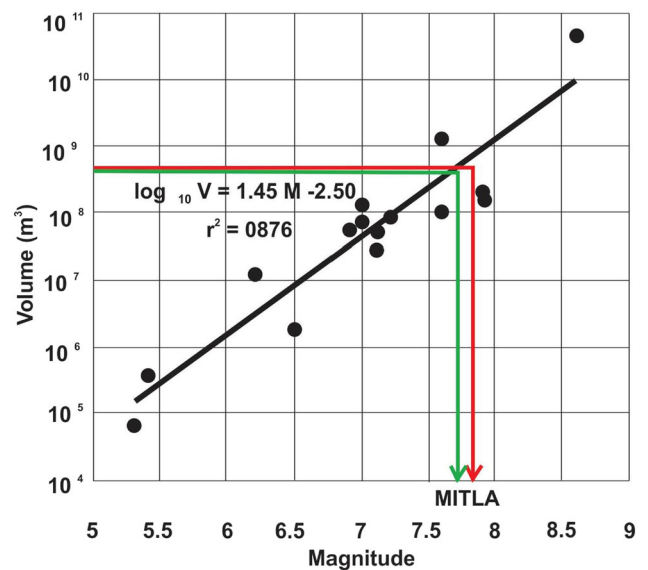
**FIGURE 10** Record of the earthquake in the accelerogram used to study Mitla as an analog [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

**TABLE 1** Data of the earthquakes used to model the Mitla collapse

Data of the seismic station	
Name of the station	Oaxaca Facultad de Medicina
Station code	OAXM
Station location	Fuente de las 7 regiones, 2 km from the center of Oaxaca City
Station coordinates	17.082872 N - 96.718744 W
Elevation (masl)	1600
Soil type	Alluvial
Institute in charge	Instituto de Ingeniería UNAM
Data of the quake	
Date (GMT)	1978/11/29
Epicenter time (GMT)	19:52:47.3
Magnitude	7.80 Mw
Epicenter coordinates	16.000N-96.690W
Local depth (km)	19
Source of epicenter data	S. K. Singh (IG)

attrition during transport), we suggest that the deposit is a typical dry rock avalanche. In fact, the coefficient of friction ( $H/L = 0.39$ ) also suggests a dry origin for the landslide (Dade & Huppert, 1994). The internal aspect of the rock-avalanche deposit does not reveal sub-rounded to rounded blocks nor voids in the fine-sized matrix that would support the presence of water during transport typical of debris flows. Another important aspect of the avalanche deposit is that it comprises fresh ignimbrite blocks and, therefore, no intense alteration or weathering of the rocks could have favored the collapse. Taken collectively, these features strongly support the argument that the collapse was not triggered by rainfall. Therefore, it is quite probable that the cause of the rock avalanche may be of seismogenic origin.

Earthquakes are one of the most common triggers of large-scale bedrock landslides, as documented worldwide (Strom & Abdurakmatov, 2018). Earthquakes and landslides are often linked, because earthquakes cause fracturing and destabilization of solid rocks weakened by their rheology, their strata geometry, or water saturation, and, occasionally, also entail the remobilization of rocks (Bommer & Rodríguez, 2002; Rodríguez, Bommer, & Chandler, 1999). Earthquakes of moderate or high magnitude can trigger landslides that sometimes cause human deaths and significant infrastructure damage. It has also been established that massive landslides can be triggered by the combination of a shift in pore pressure caused by rain or a mild earthquake. Keefer (1984, 1994) concluded that earthquakes can cause different mass movements in different geological environments and that the geology influences each movement in a different manner. More vulnerable environments are usually highly fractured, weathered, sheared, or soft rocks. Volcanic ashes, noncohesive residual soils, and alluvial and colluvial deposits are also susceptible. Keefer (1994) developed a chart to assess the

**FIGURE 11** Calculation of the probable magnitude of a possible earthquake that could have triggered the Mitla's landslides (following Keefer, 1984). The red arrow corresponds to the Mitla rock avalanche and the green arrow to the NW Mitla rock avalanche [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

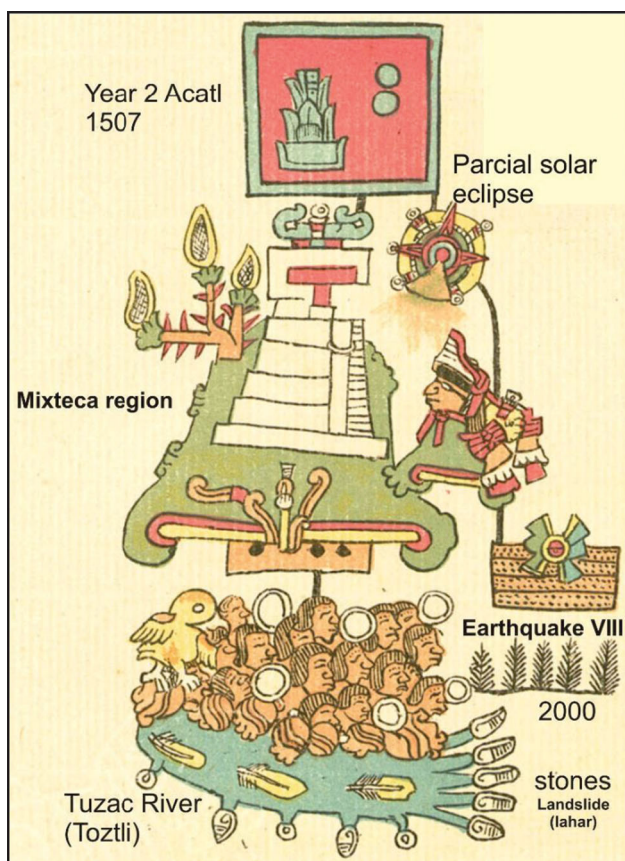
relationship between earthquakes and the volume of the sediments produced by them. Even though it was difficult to identify the exact number of landslides per earthquake, Keefer (1984,1994) showed that there is an approximate correlation between the number of landslides and the magnitude of the earthquake. Thus, an earthquake of Magnitude below 6.0 can trigger hundreds of slope faults, whereas one above 7.0 can cause thousands of faults in a rocky mass. Interestingly, by introducing the values of the rock avalanche volumes ( $m^3$ ) of the two Mitla landslides in Figure 11, we can see that a  $>7.5$  magnitude earthquake would be necessary to trigger these landslides. Earthquakes of this magnitude are not unusual in southern Mexico; in fact, just recently, two large magnitude earthquakes have occurred in the Oaxaca region: on September 7, 2017 (8.2 Mw) and February 16, 2018 (7.2 Mw; Melgar, Ruiz-Angulo, & García, 2018). Both earthquakes caused deaths and material damage in the states of Guerrero and Oaxaca. For the central zone of the state of Oaxaca, Zúñiga, Suárez, Figueroa-Soto, and Mendoza (2017) reported recurrence intervals of 37 years for earthquakes of magnitude  $\geq 7.5$  Mt for the coupling zone of the Cocos and North American Plates.

## 6.2 | Earthquakes and archaeology

Earthquakes and archaeology may, at first glance, appear as two entirely different fields of research; however, in Mesoamerica, as in Mesopotamia, Egypt, Greece, and Anatolia, archaeological remains provide evidence of seismic activity during ancient human history. García Acosta and Suárez-Reynoso (1996) assessed the impact of seismic events on pre-Columbian cultures in México for the first time. During the past 20 years, archaeoseismology (Giner-Robles,



Rodríguez-Pascua, Silva, & Pérez-López, 2018; Stiros & Jones, 1996) has introduced new approaches to study the effects of past earthquakes and, therefore, their impacts on ancient cultures. Earthquakes have been and remain frequent in the history of Mesoamerican cultures. In the Zapotec language of the Oaxaca region, they were called *xòo*, and in the Nahuatl language of central Mexico, *ollin* (movement). One of the field-excursion books of the 1906 International Geological Congress in Mexico referred to a Mitla earthquake that occurred in 1495 by using the symbols of the Codex Mendoza. More recently, Garduño-Monroy (2016) described 12 seismic events recorded with a *tlalollin* in the codex Telleriano-Remensis. The most powerful of them occurred in 1507 (“año dos cañas”) with a VIII intensity (Figure 12), causing an avalanche of water, mud, and stones (debris flow) that killed more than 2,000 warriors in the River Tuzac. A modern analog of this event is the 5.4-magnitude earthquake that occurred on June 6, 1994, southwest of Nevado del Huila volcano, Colombia (Ávila et al., 1995). This earthquake produced thousands of landslides that poured into the Paez River, producing a massive wave of mud that traveled more than 120 km downstream and killed 274 people (Scott, Macias, Naranjo, Rodriguez, & McGeehin, 2001).



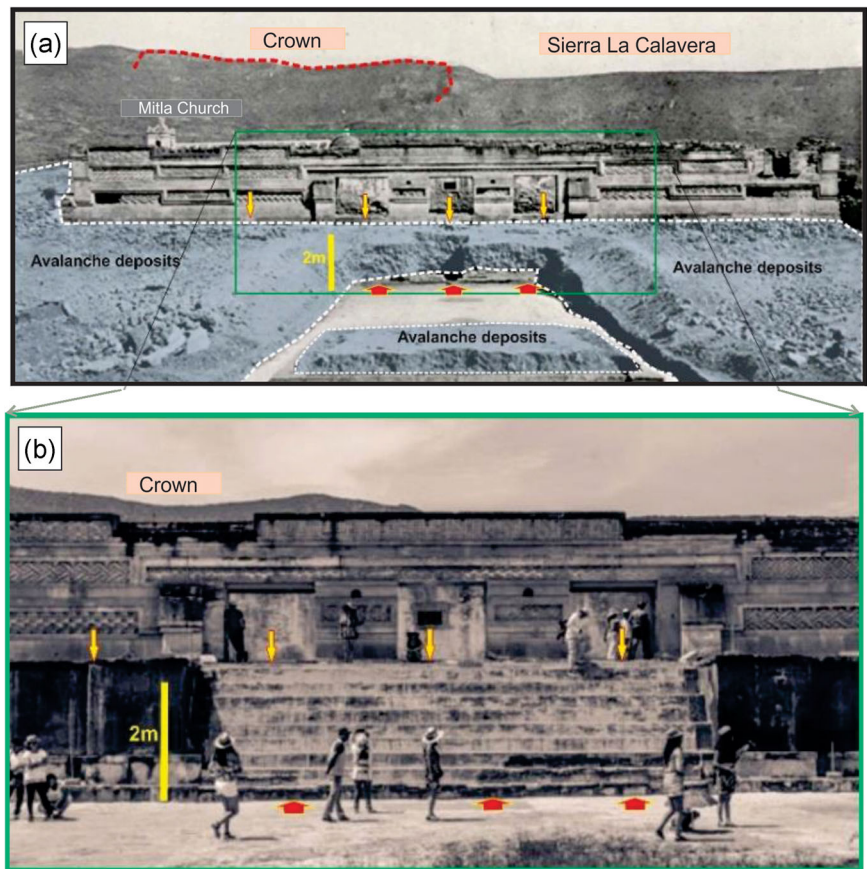
**FIGURE 12** Fragment of the Codex Telleriano-Remensis representing a prominent earthquake linked to the tragic death by drowning of 2,000 warriors in the year 1507 in the Mixteca region. The warriors were carried away by a flow of water with stones (debris flow) occurred in the Tuzac River and that was likely associated with a landslide (Garduño-Monroy, 2016) [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]

During his studies in the Mitla area, Beals (1933) recognized that the archaeological site was constructed employing earthquake-resistant techniques. He states that “Though some have almost entirely disappeared through the use of the stone for building purposes, others are in an excellent state of preservation and show few effects of the frequent violent earthquakes of the region”. In fact, as we have mentioned, Mitla sits in a highly seismic zone affected by subduction and/or intraplate related earthquakes. The La Calavera NW–SE striking fault is a normal fault with a left-lateral component. Around Mitla, the accumulated slope relief of this fault is almost 400 m, with a length of approximately 13 km. These characteristics suggest that the fault itself may have triggered an earthquake of Mw 7, although faults of this length generally cause earthquakes with magnitudes between Mw 6 and 7. It has also been suggested that similar seismogenic landslides have caused volcanic debris avalanches at El Estribo Volcano in the Lake of Pátzcuaro Pola, Macías, Garduño-Monroy, Osorio-Ocampo, and Cardona-Melchor (2014), and Jocotitlán volcano in Central México (Siebe, Komorowski, & Sheridan, 1992).

### 6.3 | Age of the collapse

Unfortunately, as no charcoal or organic soils have ever been found within the landslide deposits,  $^{14}\text{C}$  dating was not possible. Nonetheless, to try to place the timing of the natural event that impacted the Mitla site, we have used photos, prints, drawings that were available and historical information. The composite photograph in Figure 13a show the remains of Mitla before site restoration (photographed by Corner in 1899). Here, parts of the archaeological remains seem to be covered by sediments that look like the distal rock-avalanche. The image captured in 1902 shows the distal deposits of the rock avalanche lacking large blocks and the presence of a finer matrix (see Figure 14). The picture of Figure 13a also shows that the stairs (red arrows) were partially covered by over 2 m-thick deposits. In Figure 13b, two images are combined; one is a print from the 19th century, the other a recent image obtained from Google Street View (May 2011). Collectively, Figures 13 and 14 show how the Mitla archaeological site, in this case, that of “Las Columnas” was partly covered by detrital deposits, almost certainly associated with the rock-avalanche deposit. Our geophysical explorations suggested the presence of remains or walls of Mitla buildings that were probably buried by the rock avalanche. From this information, we suggest that the Mitla landslide was a historical event during which the more distal rock-avalanche deposits covered a part of this important archaeological site. This hypothesis is further supported by the fact that the entire surface of the landslide contains very few ceramic shards; consequently, it seems unlikely that the pre-Columbian city would have been built later—after the landslide—on top of the deposits, as currently stated in the official literature pertinent to the restoration of Mitla archaeological site. Evidence of the reuse of ashlar and fine-cut blocks—presumably from the former facades of buildings—for the construction of drainage works of a courtyard during the Late post-Classic (1200–1521A.D.; Robles García, Ramírez-Castilla, & Bautista-Hernández, 1995) suggests that the reused materials came

**FIGURE 13** (a) Composite of two photographs taken in 1899, and a recent image from Google Earth. (b) Combination of a photograph taken in 1902 (upper) with a recent one (lower) taken close to the same location. These images show how Mitla was covered by near 2 m of rock-avalanche deposits [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]



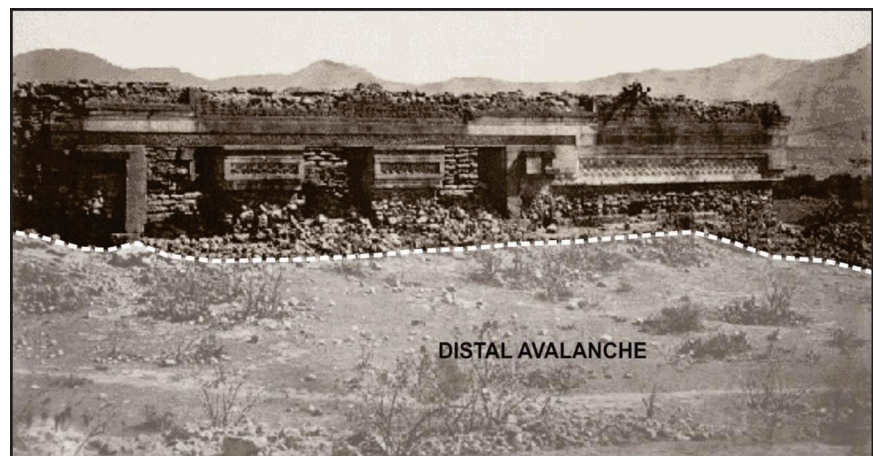
from the partial destruction of highly esteemed, pre-existing buildings. Was the cause of this destruction related to some natural disaster, such as perhaps a landslide?

From historical information, it is clear that Mitla approximately 900 A.D. had become an important site of rituals related to death as well as a major trade center for commercial exchange between the Central Mexican Altiplano, Oaxaca Valley, Tehuantepec, Soconusco, and Guatemala. Mitla's geographical location, together with cultural roots among the Zapotecs of the Central Valley region of Oaxaca, led to its growth and prominence. Also, during this era, a distinctive

architectural style emerged that involved the use of finely detailed ignimbrite stone for buildings. Tombs were an important element in this spatial concept, which gave rise to a tradition of construction with extraordinary decorative detail. From nine tombs found so far around Mitla, only Tomb 3 contained organic material that was dated at  $1,110 \pm 110$  A.D. with the  $^{14}\text{C}$  method (Bernal, 1963).

Some additional inferences about this important geological event can be deduced from historical documents. According to the Telleriano-Remensis Codex, an important earthquake struck the region of Oaxaca in 1495; from the tlalollin symbol, this event would

**FIGURE 14** Picture of the Mitla archaeological site taken at the end of the 19th century. The bottom image was taken by Corner (1899). These photographs clearly show the surface of the distal rock-avalanche deposits that partly covered the remains of Mitla before the beginning of the excavation and restoration of the site [Color figure can be viewed at [wileyonlinelibrary.com](http://wileyonlinelibrary.com)]





correspond to an earthquake of intensity between VII and VIII (Garduño-Monroy, 2016), certainly powerful enough to trigger the Mitla landslide. In addition, 18th century documents owned by Brother Francisco Ajofrín indicated that conquering and subjugation actions undertaken by the Aztec emperor Ahuizotl (1486–1502) occurred in a bloody battle in the year 1494 (Ajofrín, 1964). This evidence allows us to further narrow the timing of the Mitla landslide between 1494 and 1521 A.D. (Spanish conquest). These observations recorded in historical documents may help explain the generally weakened condition of the ancient city of Mitla that existed when the Spaniards arrived, suggesting that the landslide had occurred not long ago. Upon their arrival, the Spaniards only found ruins at Mitla, and because of the cultural importance of the city, Christian religious structures were quickly built on the pre-Hispanic remains. In addition, the construction of the city of Tlacolula was planned, to serve as a new center on a highly important trade route for the Spanish.

Archaeologists report that, during its prime, Mitla had a population of about 10,000 people, a figure equal to the current population of the present-day city, which covers an area over 1.5 km<sup>2</sup>. However, if we consider the five remaining pre-Columbian buildings, the total area of ancient Mitla at the time was 0.18 km<sup>2</sup>, which is too small of an area to hold 10,000 people, thereby further suggesting that other parts of the ancient city are also buried by the rock avalanche. With our hypothesis, only targeted, precise archaeological and geophysical surveys can provide new insights on the impact of the landslide on the Mitla ceremonial center.

In fact, it is possible that the landslide event may have caused deaths among Mitla's population, which may have contributed to naming the place (in Nahuatl Mictlan, in Mixteco Ñuu Ndiyi, or "Place of the Dead"), notwithstanding the characteristic ritual tombs found during the excavations.

## 7 | CONCLUSIONS

Based on the geological, geomorphological, and geophysical evidence, we propose a seismogenic origin for the Mitla landslide. The Etna Valley is part of the regional Oaxaca-Tehuacán fault system that has been seismically active in its geologic history. The NW–SE La Calavera fault is part of this system and presents morphologic evidence (collapse scars) of a currently active component. The collapse was likely caused by a large earthquake (probable magnitude of Mw 6–7.4) that triggered two dry landslides ( $H/L = 0.37$ ) with a total combined volume of approximately 0.2 km<sup>3</sup>. The photographic archive indicates that this event must have occurred after the ceremonial center was built, which corresponds broadly to the post-Classic period (900 and 1521AD), before the arrival of the Spaniards. The Codex Telleriano-Remensis recorded an occurred earthquake in 1495 in the Oaxaca area with intensities over VII on the scale ESI2007 (see Garduño-Monroy, 2016). With this new evidence of an avalanche that covered part of the pre-Columbian town of Mitla, the history of the great Zapotec civilization should be re-analyzed. Under the present active tectonic setting, similar events could happen in the future and, therefore, it would be prudent to implement a more precise

seismic monitoring of the region, and to develop a strategic and focused restoration plan for the archaeological site.


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## DATA AVAILABILITY STATEMENT

Data available on request from the authors. The data that support the findings of this study are available from the corresponding authors upon reasonable request.

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