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Geohistory and geomorphology of the Mitlatongo landslide, Oaxaca, Mexico

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Abstract When a landslide occurs, the landscape is radically transformed; a pristine, unexplored geography emerges, with new morphogenetic processes. When the event also affects human settlements, it is crucial to understand all the physical and geographic factors that explain it and all its multiple social implications. In September 2011, a landslide occurred in the Mitlatongo Valley, rendering more than 400 homes unusable and forcing the displacement of more than 1,500 people living there. The trigger was intense and prolonged rains that saturated the soil in a geologically unstable area. Despite the significance of the event, very little documentation is available. This information is not only limited to the landslide but also to the historical background of Mitlatongo, as it is a settlement with pre-Hispanic origins. For this reason, this work presents a geohistorical analysis based on a detailed geomorphological and geological map, which documents the transformations of the landscape before and after the disaster. To this end, the study integrates multiple sources of information (historical aerial photographs, archival documentation, local testimonies, and drone photogrammetry), processed and analyzed using GIS to reconstruct the geomorphological dynamics before and after the event. The geomorphological map reveals the complexity of the landslide, distinguishing three sectors: scarp areas, accumulation zones, and pre-existing fractures. Five main units were identified within the landslide, with ground displacements of up to 225 meters. Geological mapping highlights the interaction between tectonic structures, such as the Tres Lagunas-Santa Cruz fault and the Pueblo Viejo syncline, and the processes of erosion and soil saturation. Taken together, they provide a comprehensive perspective on the event and its impact on ground dynamics. This paper also highlights the social impact of the landslide, which resulted in an ineffective government response, leaving the community in precarious conditions.

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Introduction

As September 2011 began, after several days of intense and relentless rain, the residents of the Mitlatongo Valley were astonished to see the soil they had inhabited since pre-Hispanic times cracking open with massive fissures. This marked the onset of a devastating landslide that ultimately forced them to abandon their land.

In countries with emerging economies such as Mexico, hillslope processes have devastating effects that disproportionately affect the most vulnerable socioeconomic groups. Due to a lack of safe and well-planned land, these communities often reside in high-risk areas, such as unstable slopes or regions near rivers (Alcántara-Ayala, 2025; Alcántara-Ayala et al., 2018; Pourghasemi et al., 2020; Quesada-Román, 2022). Poor infrastructure and the absence of effective mitigation measures increase vulnerability, resulting in loss of life, damage to housing, and disruption of livelihoods (Valdés Carrera et al., 2023; Acosta-Quesada & Quesada-Román, 2025). Moreover, constrained resources hinder quick responses and reconstruction efforts after such events, perpetuating the cycle of poverty and vulnerability to disasters (Ogunmakinde et al., 2024; Wisner & Luce, 1993). These impacts highlight the necessity for inclusive land-use planning policies and risk management strategies that prioritize the most vulnerable communities (Murillo-García et al., 2017; Rey & Casimiro, 2023).

In Mexico, 93% of landslide events, such as those in Mitlatongo, are triggered by hydrometeorological factors related to rainfall, storms, or cyclones (Díaz et al., 2020). The State of Oaxaca is among the regions with the highest frequency of mass wasting processes in both Mexico and Central America (Dávila et al., 2021). The mountainous area of the Mixteca Alta, where the Mitlatongo Valley is located, has a historical susceptibility to hillslope processes. Various phenomena, including earthquakes, floods, and hurricanes, combined with the highly marginalized status of many localities vulnerable to disasters, have historically caused significant damage to the population.

To understand the phenomenon of mass movements in the Mixteca Alta, it is essential to consider the involved physical geographical factors (sensu Guns & Vanacker, 2014). The region features a rugged relief with steep slopes that facilitate the detachment of materials. The present rock types are easily erodible, contributing to terrain instability. This includes prevalent soft sedimentary rocks, along with highly weathered metamorphic and igneous rocks. Soil characteristics also do not aid the situation; some soils have a loose texture and low cohesion, while others are clayey and sandy, with minimal organic matter. In terms of climate, the region experiences intense rainfall concentrated from May to October (Cuervo-Robayo et al., 2020; Onofre Villalba et al., 2023). These rains can be heavy and prolonged, saturating the soil, increasing its weight, and promoting the likelihood of landslides. This process has resulted in a landscape of significant geomorphological complexity in the Mixteca Alta (Hernández-Santana et al., 2009). Additionally, it is important to highlight that Oaxaca has the highest frequency of tectonic movements in Mexico (SGM, 2017), which further contributes to the occurrence of mass wasting processes.

Furthermore, we must consider the historical management of the land by the local inhabitants (González-Abraham et al., 2015). It is important to mention that this region has been inhabited for approximately nine thousand years, making it demographically dynamic throughout its history. It reached its peak during the Mesoamerican Postclassic period (900–1520) (González Leiva, 2012). Archaeological sites such as Guixonachapa in San Andrés Ixtlahuaca reveal infrastructure designed to mitigate mass wasting processes, utilizing stone walls (Gómez Martínez, 2007). Evidence of human activity in this region dates back thousands of years, showcasing sophisticated agricultural practices adapted to its mountainous and arid environment. The Mixtecs and their ancestors developed innovative techniques to maximize production, manage water, and conserve soil by constructing agricultural terraces (*lama-bordos*), canals, and irrigation ditches (Spores, 1967; Leigh et al., 2013; Pérez-Rodríguez, 2016; Santiago-Mejía et al., 2018). However, shifts in agricultural dynamics, the opening of new lands for high-demand crops, and overgrazing since the colonial period have contributed to the ongoing deforestation of the slopes. This issue is particularly pronounced in the Mixteca Alta and has led to an increase in landslides.

This paper examines the hillslope processes that occurred in the Mitlatongo Valley. This geographic space, with a remote dimension and difficult access (sensu Bocco, 2016), holds much information that has not yet been documented regarding both the mass movement itself and the historical context of its residents until 2011, when they were compelled to abandon the village.

According to local accounts, the phenomenon began to manifest slowly during the first days of September 2011. The persistent rains saturated the soil, particularly on the northern flank known as Peña Colorada (see Fig. 1). This saturation led to rockslides in the rupture zone. It facilitated the displacement of the terrain toward the south, where the two towns of Santiago Mitlatongo and Santa Cruz Mitlatongo were located. As a result, cracks and sinkholes began to appear, gradually increasing in both quantity and size, with some reaching lengths of 80 meters and depths of 3 meters (Domínguez and Reyes, 2012; López Salazar, 2016).

Previous geophysical studies (Dominguez and Reyes, 2012; Dominguez et al., 2013; Gonzalez and Lopez, 2016) indicated that the landslide was influenced by both geological structures and hydrometeorological factors. The valley is situated in a mountainous area comprised of unconsolidated, water-saturated sediments resting on a more rigid layer of limestone rock. Heavy seasonal rains caused excess water to accumulate in the soil, which increased pressure on the already vulnerable slopes and ultimately triggered the hillslope process. Additionally, deforestation, local tectonic movements,

Fig. 1 Rupture zone located on the northern flank beneath Peña Colorada hill, February 2021

and the absence of preventive measures could have contributed to the terrain's instability.

The 2011 landslide in the Mitlatongo Valley swept away the two villages located there, destroying over 400 homes and displacing approximately 1,500 people to temporary camps. The government declared the area high-risk (SEGOB, 2011) and relocated residents to "Santa Cruz Mitlatongo Nuevo", but bureaucratic inefficiencies and alleged corruption hindered reconstruction efforts (López López, 2021; Ortíz, 2015; Quadratín, 2013). In addition to the above, the disaster ruined the valley's agricultural capacity, the main means of livelihood for the locals, which reinforced the precariousness of the local economy and food security (López Salazar, 2016; Ruiz Arrazola, 2011). Over time, residents adapted to the altered landscape for farming, but emotional and cultural losses persisted, with displacement disrupting traditional religious and social practices (Neira Castro, 2020; Rodríguez Cruz, 2015). More than a decade later, the community faces aging demographics, inadequate infrastructure, precarious living conditions, and youth out-migration, leaving it reliant on government aid.

In short, the 2011 Mitlatongo landslide was a significant event from a geographical perspective and of extreme gravity due to its social impact. The information developed to date is invaluable and represents the starting point for this investigation, but no major study has thoroughly analyzed its origin or the current conditions of the valley and its inhabitants.

First, there is a lack of geological mapping at an appropriate scale to understand the valley's structural layout. Second, rainfall, the primary factor that triggered the mass movement, has not been adequately documented, as previous studies do not provide specific data for the months leading up to the event or for the prior years. Third, the geomorphological changes resulting from the landslide have modified Mitlatongo's topography and surface water network, which also requires a detailed mapping.

Lastly, regarding the historical context, limited historical information and cartographic data are available for both towns, which have pre-Hispanic origins. This study aims to shed light on the events surrounding the Mitlatongo mass movement, a disaster that irreversibly marked a community of more than 1,500 people and that continues to pay its consequences to this day.

Materials and methods

The geohistorical perspective adopts an anthropocene and interdisciplinary approach (sensu Tarolli et al., 2014) to analyze the interactions between natural changes and social development, highlighting how communities understand, transform, and appropriate their landscapes over time (Bianco, 2019; Metzger & Reghezza-Zitt, 2019; Franch and Urquijo, 2020). Giacona et al. (2022) identify three key characteristics of geohistorical research: (1) it integrates the approaches, questions, and methodologies of both historians and geographers; (2) it employs a diachronic perspective that facilitates the study of changes over time; and (3) it allows for the joint analysis of spatial dynamics among various elements within a system, along with their corresponding temporalities, addressing both continuities and changes.

In the case of Mitlatongo, a geohistorical methodology is employed to analyze mass movements by incorporating historical, geographical, cartographic, and social data. This approach enhances our understanding of how environmental characteristics and human actions jointly shape the occurrence of mass wasting processes and their associated social impacts. The geohistorical approach to analyzing natural hazards is not a new concept (Bravard, 2004; Combe, 2009; Franchomme et al., 2014; Metzger & Reghezza-Zitt, 2019; Giacona et al., 2022). Natural phenomena are influenced by political constructs, allowing for an exploration of societal vulnerabilities and responses over time. The geohistorical narrative approach offers a dynamic understanding of how territories and their inhabitants adapt to or are affected by these risks, ultimately highlighting the social reality experienced by populations following such an event.

The geological configuration of the study area has been verified through field examinations of rock samples. We performed several systematic drone flights, covering the area from west to east and north to south, while gathering structural data around the mass movement. These data were processed using GIS, which enabled comprehensive photointerpretation and was essential for developing a detailed geological and geomorphological map of the landslide area.

The geomorphological map of the Mitlatongo landslide and all historical compilations of the valley were created through the following stages: The first step involved gathering preliminary information from various sources, including historical archives (such as the Archivo General de la Nación, Archivo Histórico del Estado de Oaxaca, and Mapoteca Orozco y Berra), press reports, previous geophysical studies, INEGI cartography, and aerial photographs. Previous geophysical works was based on gravimetric studies (measurement of small variations in Earth's gravity caused by density differences in rocks), seismic refraction methods (waves emitted in the ground that change speed as they pass through different layers), and vertical P-wave reflection (waves bounce off deeper layers, identifying the geometry of faults or discontinuities) (Domínguez and Reyes, 2012; Domínguez et al., 2013; González and López, 2016). These measurements were essential for identifying the depth of fault surfaces, locating tectonic structures, and recognizing the influence of geohydrology on the process.

The second stage of this research was field data collection, which included recognizing the affected area, identifying geomorphological characteristics (such as slopes, soil types, and vegetation), assessing the present material types (including sediments and rocks), evaluating slope inclinations, conducting drone flights over the washed-out tongue, documenting the area photographically, and interviewing residents. In the third phase, GIS work was utilized for geomorphological analysis. This included terrain modeling, characterization of the landslide types, and creating a geological map (sensu Franch-Pardo et al., 2023). Finally, cartographic outputs were developed, resulting in the edition and design of the maps presented in this study.

For the geomorphological reconstruction prior to the landslide, two sets of historical aerial photographs belonging to the Antonio García Cubas Library of the Institute of Geography at UNAM were used. The primary image corresponds to flight E14D46A from 1995, composed of an 8-bit panchromatic band with dimensions of 7050 × 6050 pixels. This file has a spatial resolution of 2 m per pixel, which allowed its integration into the GIS through georeferencing. As secondary support, an analog aerial photograph from flight INEGI CNAS-2136-A, taken in March 1979, was used. This photograph is in a 23 × 23 cm panchromatic format with an approximate scale of 1:30,000. This image was digitized by high-resolution scanning for comparative analysis. Together, both sources enabled the interpretation of the valley's morphology before the 2011 landslide.

For the extraction of current photogrammetric data, drone flights were conducted in 2019 and 2021. The 2019 flight, covering a 3 km displacement area, used four DJI drones (Phantom 4 Pro and Mavic 2 Pro) to produce an orthomosaic and a DEM with resolutions of 5 and 10 cm/pixel. The 2021 flight employed a DJI Phantom 3 drone using a Point of Interest (POI) method to capture 68 overlapping oblique images, generating a high-resolution (10 cm/pixel) Digital Elevation Model (DEM) of the rupture zone. Conducted manually for battery efficiency, the flights maintained a 120-meter altitude and captured 2,000 images with 70% overlap, processed using Agisoft Metashape.

Historical and geographical context

The small towns of Santiago Mitlatongo, located in the municipality of Asunción Nochixtlán, and Santa Cruz Mitlatongo, situated within the municipality of Magdalena Jaltepec, are found in the Mixteca region of the state of Oaxaca (Fig. 2). This region encompasses approximately 40,000 square kilometers, covering the western part of Oaxaca, the southern portion of Puebla, and parts of eastern Guerrero. The boundaries of the Mixteca region are defined by ethnic and historical-territorial factors, reflecting the areas influenced by Mixtec lordships during the time of the Spanish Conquest in the 16th century.

Within the Mixteca region, three sub-regions can be identified, whose main population centers were former novo-Hispanic head towns: the Mixteca Alta, which includes Yanhuitlán, Tlaxiaco, Nochixtlán, and Tilantongo; the Mixteca Baja, headed by Achiutla; and the Mixteca Costa, with Tututepec as its main historical hub. Most of the population recognized as Mixtecs, referred to as ñudzahui in their native language, resides in the western part of the region (Hermann-Lejarazu, 2015; Spores, 1967; Terraciano, 2004, 2013).

Regionally, this area is characterized by a series of highlands, with elevations ranging from sea level to 2,300 meters (9,800 feet). The climate is temperate and semi-arid, with an average annual temperature of around 19 °C. Most of the region is covered by pine forests, pine-oak forests, and deciduous oak forests,

Fig. 2 Location of Mitlatongo in the Mixteca Alta, Oaxaca, Mexico

some degree of disturbance, in a mosaic with patches of grasslands and rainfed agriculture.

Santiago Mitlatongo and Santa Cruz Mitlatongo, located in the area known as Mixteca Alta, shared the same territory (fig. 2). They apparently featured a dual-head town and two doctrines, whose patronages correspond to their Christian toponyms—Santiago and Santa Cruz. The indigenous toponym, Mitlatongo, comes from Nahuatl, which served as a lingua franca during the early colonial period; as a result, the original Mixtec name has been lost. In Nahuatl, Mitlatongo translates to “in the small place of the dead”.

The foundation of the population in the valley is usually traced back to the year 1444 (López Salazar, 2016). In Mixtec cosmology, specifically in the foundational myth of Mitlatongo, King Camanderú resided on Monterrey Hill and competed against other regional kings, including the king of Tilantongo. Through his cleverness, he triumphed in ritual competitions and expanded his dominion significantly. In contemporary traditions, Camanderú is regarded as a protective figure who brings rain and dispels storms. He is also celebrated as a cultural hero who delivered corn, palm trees, and fruit trees to his people (Barabas, 2020).

During the 16th century, Mitlatongo was deeply affected by the colonization process and served as an encomienda for the conquistador Gerónimo Ruiz de la Mota y Zárate. Around 1560, his son, Antonio de la Mota, inherited this property. Antonio’s grandson, Antonio, is listed as a beneficiary of the indigenous tribute from Mitlatongo between 1597 and 1604. This tribute continued to be directed to a private individual until at least 1623.

Administratively, Mitlatongo fell under the jurisdiction of the mayor of Teposcolula, at least since

1553. Documentary sources indicate that at that time, Mitlatongo comprised five neighborhoods and five ranches. In 1566, both Mitlatongo and the neighboring town of Tamazola changed their jurisdiction to Tilantongo, which that same year became directly owned by the Spanish Crown as a corregimiento (Gerhard, 1986). Regarding the population of Mitlatongo during this period, the Suma de visitas (Sum of visits) reports that its residents worked in a lead mine near the valley (Forde, 2022).

Due to the geographical distance between Tilantongo and its subject towns relative to the administrative-territorial hubs, the corregimiento began to decline by the eighteenth century. As a result, during the period of independence, Tilantongo became a municipality under the jurisdiction of the Nochixtlán Party. In the twentieth century, with the establishment of the free municipality, Tilantongo was officially recognized as such. Still, it did not regain the territorial hegemony it may have possessed in pre-Hispanic times or the early years of the novo-Hispanic period. Consequently, the towns affiliated with Mitlatongo were incorporated into different municipalities: Asunción Nochixtlán and Magdalena Jaltepec.

In the historical documentation presented in this work, we obtained a record of disasters in Mitlatongo from the work of Martínez Gracida, in his work Synoptic, Geographical, and Statistical Table of the Free and Sovereign State of Oaxaca (Cuadro sinóptico, geográfico y estadístico del Estado Libre y Soberano de Oaxaca) (1883). This document details a severe storm that occurred on April 8, 1843, which significantly impacted Mitlatongo, resulting in fatalities (González Pérez, 2019; Martínez Gracida, 1883a, 1883b).

Geologic context of the Mitlatongo area

The Mixteca region is one of the oldest geological areas in Mexico. It is where the Sierra Madre Oriental, Eje Neovolcánico, and Sierra Madre del Sur converge, forming the so-called Nudo Mixteco. This area has experienced a strong process of erosion and faulting, which has modified the courses of rivers such as the Balsas, Lerma, and Papaloapan. Volcanic activity was intense, and rivers created deep canyons that contributed to the complexity of the relief (Domínguez and Reyes, 2012).

In the region, different geological units are mainly represented by the following: (1) undifferentiated Cretaceous rocks of the Albian-Cenomanian age, which are composed of limestone and dolomite (Fig. 3); (2) undifferentiated Cretaceous rocks of the Turonian-Maastrichtian age, consisting of limestone and shale; (3) undifferentiated polymictic conglomerate-sandstone of Paleocene-Eocene age; and (4) scarce Dacitic-Andesitic rocks of Oligocene age, not outcropping in the study area, but near to the southeastern sector (SGM, 2007).

The regional structural setting is characterized by a highly deformed sequence that consists of a series of anticlines and synclines, with axial planes primarily oriented in the N-S and NW-SE directions. Additionally, there are regional normal faults that predominantly dip to the west. Locally, the mass movement correlates with two regional structures that fit with the east and west borders of the landslide. To the east, the core of the Pueblo Viejo syncline exhibits an angle of dip of 30° toward the east in the upper limestones. In contrast, to the west, the hillslope process is bordered

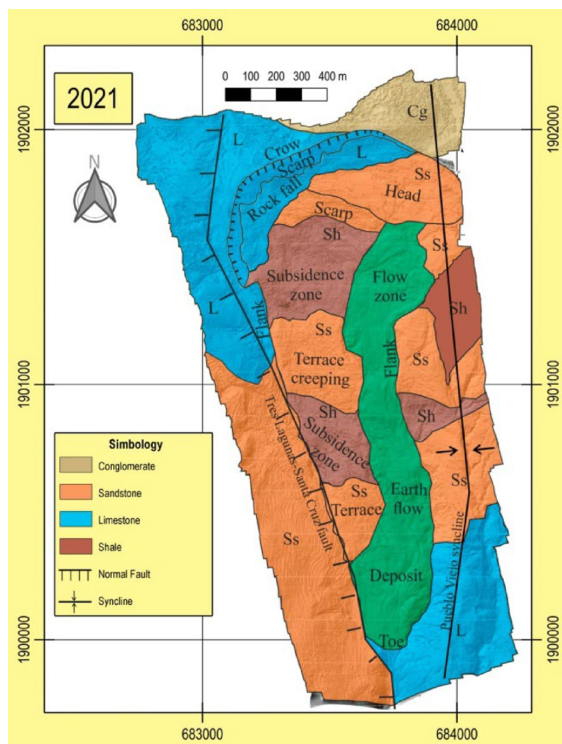

Fig. 3 Main geological and geomorphological features of the Mitlatongo landslide

by a regional normal fault known as Tres Lagunas-Santa Cruz, with a west 24° dip (SGM, 2007).

The combination of this fault, the stratification planes of the folded rocks, and existing fractures creates a wedge with intersection planes in the landslide area (Fig. 3). This configuration, along with the natural instability associated with the slope of the topography to the south, contributes to material movement toward the south-southeast. Consequently, much of the mass wasting process activity is linked to the susceptible surface geology and landforms in the region.

Climate

Rainfall is one of the main factors causing landslides in Mexico and tropical regions. Consequently, rainfall thresholds that cause mass movements have been determined based on factors such as susceptibility to slope instability, the association with total accumulated rainfall, antecedent rainfall, rainfall intensity, soil moisture index, and rainfall duration (Domínguez et al., 2016; Onofre Villalba et al., 2023). The regionalization of the Mexican territory according to its degree of susceptibility determined the presence of eight regions. In the South Pacific region, where the Mitlatongo Valley is located, critical precipitation values have been calculated for a slope instability scenario that could trigger an imminent landslide. This was calculated based on mean annual precipitation, antecedent rainfall, and their relationship with the number and conditions of recorded mass wasting processes (Munive et al., 2020). It was observed that there is a correlation between the amount of accumulated rainfall that produces mass movements and the average annual rainfall in a region, with this correlation being approximately 0.244 (Domínguez Morales and González Huesca, 2021, p. 6).

This relationship was used to estimate the minimum precipitation threshold, defined as "the amount of rainfall above which the probability of occurrence of a mass movement increases dramatically" (Dominguez et al., 2016, p. 6). The threshold value indicates the minimum amount of precipitation accumulated over a 24-hour period necessary to trigger a mass movement event. This value was calculated using the formula $Um = \bar{x}$ precipitation (mm) * 0.244, established by the National Center for Disaster Forecasting in Mexico (Dominguez and Gonzalez, 2021, p. 6). According to data from the National Meteorological Service at the Santiago Tilantongo station, which is closest to the study area and located at coordinates 17°17'17'' North Latitude and 97°22'05'' East Longitude, 12 km northwest of the site, with an altitude of 2,284 meters above sea level, the average annual precipitation for the area is 659.3 mm (SISPLADE, 2020). At the time of the study, Tilantongo station had a registration period from 1983-2017, with 18% of the data missing. The gaps in monthly rainfall were completed by calculating the average precipitation for that month based on the years with data recorded. The data from the year of the landslide studied here were complete. Tilantongo station data indicate that the minimum precipitation threshold that triggers landslides in the area is 160.8 mm.

Results

Geomorphology

The Mitlatongo landslide covers an area of 2 km^2 and stretches 2,875 m in length. Based on the P-wave vertical reflection data collected by González and López (2016) to obtain the detachment surface, we found that the volume of soil removed was approximately 70 million m^3, with a dip of 50° in the Peña Colorada fault plane and between 6° and 20° in the rest of the debris tongue (González and López, 2016), with an inclination of 50° in the Peña Colorada fault plane and between 6° and 20° in the rest of the debris tongue (González and López, 2016).

We divided the hillslope process into five large units (fig. 4): crown cracks, head, rotational landslide, translational landslide and depositional area. Starting from the highest and northernmost sector, the crown cracks (first unit) represent the steepest part and the location of the rupture area of the landslide; the fracture was already visible in the 1995 image, although it was smaller at that time. Below this is the head (second unit), which refers to the upper part of the displaced mass. The concave arrangement of the mass movement processes collects water in this section, which then flows downstream. The next section is the longest, measuring one and a half kilometers, and we divide it longitudinally into two parts: the rotational mass movement (third unit), where the displaced material slides along the detachment surface; the

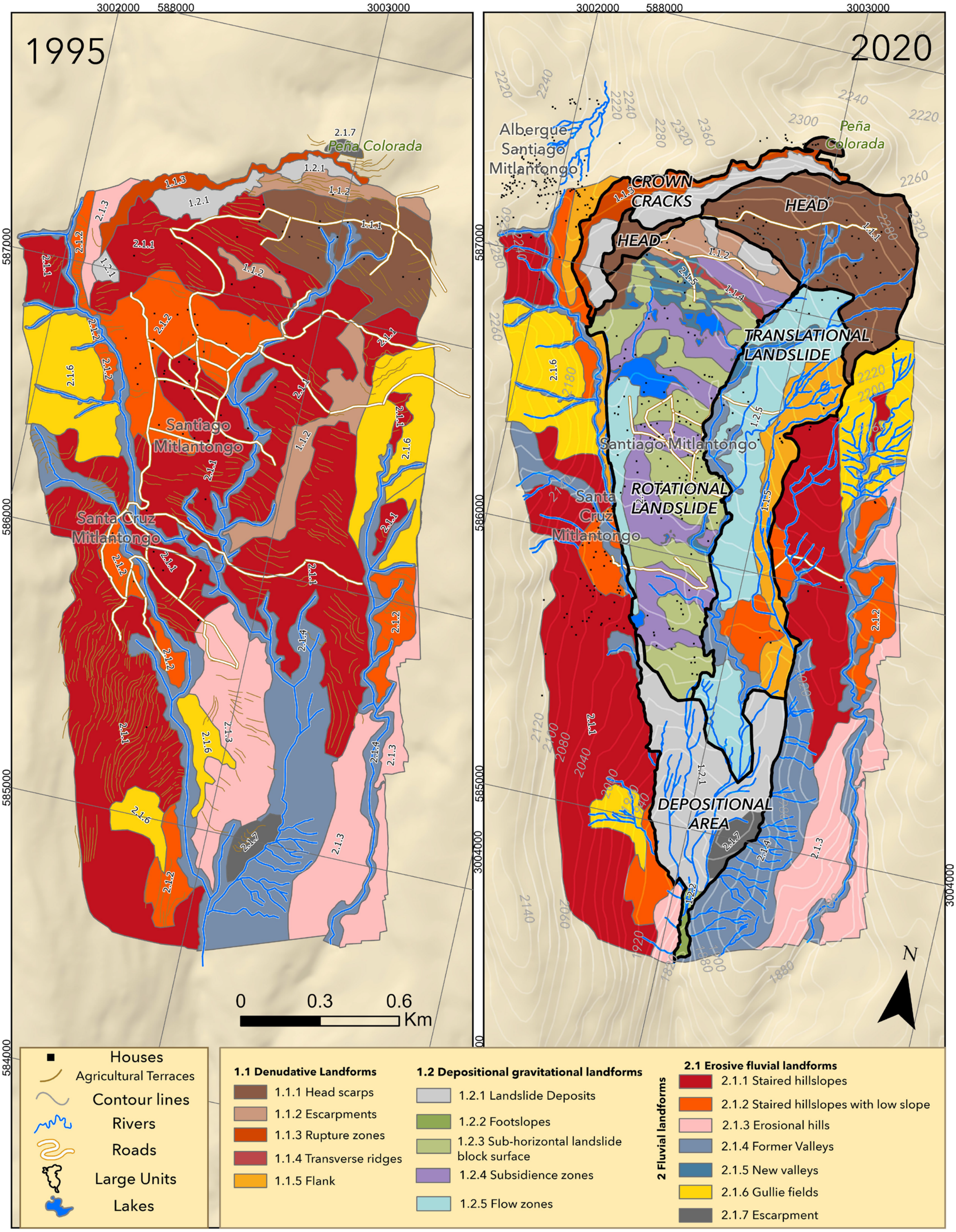

Fig. 4 Geomorphological maps of Mitlatongo landslide using imagery from 1995 and 2020. 1: 1,000 scale

upper part sinks while the lower part rises, creating undulations in the terrain. This rotation of the material generates a series of escarpments and cracks in the upper zone, while bulges and folds are formed in the lower section, thus developing a new topography. This shift has resulted in the creation of new bodies of water that did not exist before the event. Figure 6 shows the evolution of the road network in Mitlatongo between 1995 and 2020. In 1995, the road layout was dense and continuous, with multiple branches connecting the urban core with the surrounding agricultural areas. However, by 2020, a marked reconfiguration of this network was observed: several old sections ceased to exist, were interrupted, or displaced, while alternative routes emerged that seek to maintain connectivity, adapting to the new orography. The superposition of both layers reveals different types of displacement: in the upper part of the rotational landslide, the displacement was 60 meters, while in the central sector, it reached 225 meters (Figs 5 and 6).

On the right side of the rotational hillslope process, there is the translational landslide (fourth unit) characterized by longitudinal fractures and material accumulation in the lower section. Finally, the last part of the mass wasting process is the depositional area (fifth unit), or mass movement toe, where the Tres Lagunas-Santa Cruz fault converges with the Pueblo Viejo syncline (Fig. 3). This created a funnel that facilitated the accumulation and deposition of the transported material.

The geomorphological map and its analysis of the gravitational and fluvial landforms associated with the Mitlatongo landslide is presented in Fig. 4. The classification highlights the dominant geomorphic

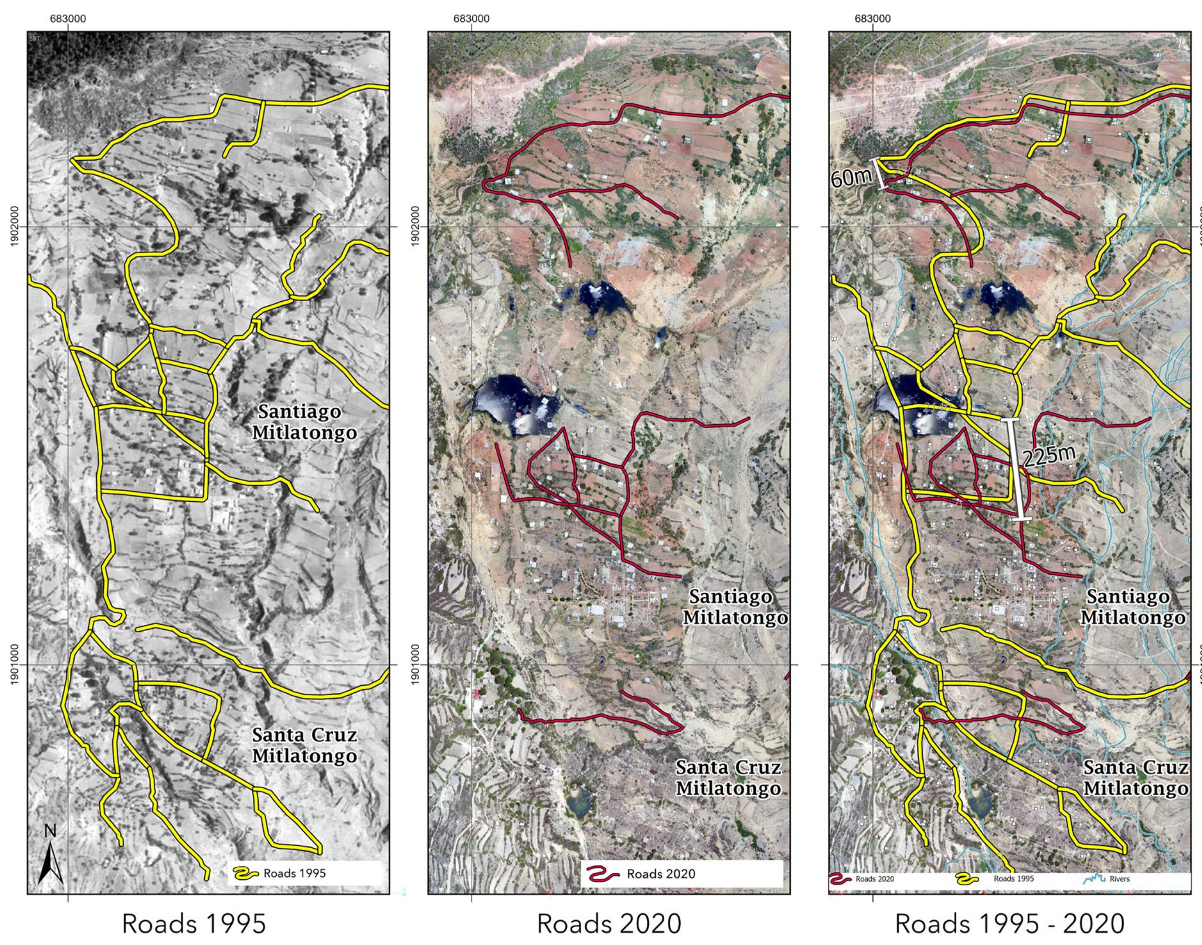

Fig. 5 Mapping of the roads visible in the 1995 image, in the 2020 image, and comparison of their displacement

Fig. 6 An image of one of the houses displaced more than 200 meters from where it was originally built. February 2021

processes shaping the landscape, distinguishing between erosive and depositional gravitational landforms, as well as erosive fluvial landforms. By examining these features, the analysis provides insight into the mechanisms driving mass movement and fluvial erosion in the region, contributing to a better understanding of the geomorphological evolution of the landslide-affected area.

Gravitational landforms

Denudative gravitational landforms

The head scarps are steep, nearly vertical surfaces located at the top of a mass movement. They signify the point of initial rupture, where the slope fails due to gravitational forces, leading to the downslope movement of material. The head scarp is generally fresh and unvegetated, indicating a recent landslide activity. Escarpments are similar to head scarps but are typically larger and older. They are long, steep slopes or cliffs formed by erosion or tectonic activity. In the context of hillslope processes, escarpments often develop as part of the gradual mass-wasting process, shaping the landscape over time. Rupture zones are areas where the earth's surface breaks apart due to gravitational stresses. In mass wasting processes, these zones often appear at the boundaries between stable and unstable material, marking the initiation of sliding or subsidence.

Transverse ridges form perpendicular to the direction of movement during a hillslope process. They often occur at the toe or along the flanks of a landslide as material accumulates and is compressed. The flank of a hillslope process refers to the side boundaries of the sliding mass. These lateral edges of the mass movement are typically less steep than the head scarp and can show signs of secondary erosion or deposition.

Depositional gravitational landforms

Landslide deposits are the accumulated materials transported downslope by landslide activity. They consist of loose rocks, soil, and debris and can vary in size depending on the magnitude of the landslide. Landslide deposits are commonly found at the base of the head scarp or along the path of the slide. Footslopes are located at the lower end of a slope. They are areas where material from gravitational movements accumulates. These depositional zones are critical in stabilizing hillslopes after a landslide, as the deposited material helps to reduce further erosion. Sub-horizontal landslide block surface are flat or gently sloping platforms that step down a hillside. They are formed by repeated hillslope processes or deposits. These geoforms often indicate a history of gravitational processes, where successive hillslope processes have deposited material at different levels.

Subsidence zones are areas where the ground has sunk or collapsed due to gravitational forces. They are often linked to the removal of underlying support, such as water drainage or sediment removal by hillslope processes. Flow zones represent areas of a hillslope process where material moves in a more fluid, chaotic manner. These zones are typically located in the middle or lower sections of the slide, where the material becomes highly mobilized and flows downward slope.

Fluvial landforms

Erosive fluvial landforms

The steep, stepped hillslopes, characterized by intense erosion, feature significant vertical drop-offs shaped by fluvial processes or surface runoff. The steep gradient enhances the erosive power of flowing water, leading to the development of a sharply stepped landscape. The gently stepped hillslopes with initial erosion exhibit a more gradual gradient, where initial erosion processes are beginning to shape the landscape. Over time, the gentle hillslopes can evolve into more pronounced terraces or steeper steps. Former valleys are old, abandoned valleys that were once active fluvial systems. They often represent relict features left behind as a river or stream changes its course due to tectonic activity or sediment deposition, leaving behind a dry or underused channel.

Landslide dynamics create new valleys, which, after the event, start a series of active fluvial processes. Rivers or streams carve through the landscape, creating steep walls and narrow floors as the water cuts through rock and sediment, often following tectonic or gravitational pathways. Ravines are small, narrow valleys with steep sides, formed by the action of running water over long periods. They are typically associated with intermittent streams or heavy rainfall that leads to rapid erosion of soft rock or sediment. Gullies are smaller than ravines and are created by water erosion on loose soils. They often signify the early stages of fluvial erosion in a region, marking the transition from sheet erosion to channelized flow. Escarpments are exposed sections of bedrock that become visible when fluvial erosion removes the overlying material. They offer significant insights into the geological history and erosive forces at work in an area.

Mitlatongo landslide triggers

The arrangement of the valley's structural geology and the continuous rainfall that occurred between August and September 2011 were the triggers of the landslide (Domínguez and Reyes, 2012; Domínguez et al., 2013; González and López, 2016). In the sedimentary context of the valley, the hillslope process was bounded by regional structures: to the east, the core of the Pueblo Viejo syncline, and to the west, the Tres Lagunas-Santa Cruz regional normal fault. The latter, interacting with folded rock layering planes and fractures, forms a structural wedge whose intersection facilitates natural instability to the east, further reinforced by the topographic slope to the south. This geological configuration caused the movement of material to the south-southeast, triggering the landslide.

Daily precipitation data from Tilantongo station indicates precipitation amounts of 5mm in the 24 hours before the event and a total accumulation of 43 mm over the 5 days before the mass wasting process. Although these values are well below the established threshold, villagers reported that the first signs of instability appeared on September 1 and 2, following several days of heavy rainfall (Dominguez et al., 2016) (Fig. 7). The meteorological record indicates that over the 10 days before the first signs appeared (from August 22 to September

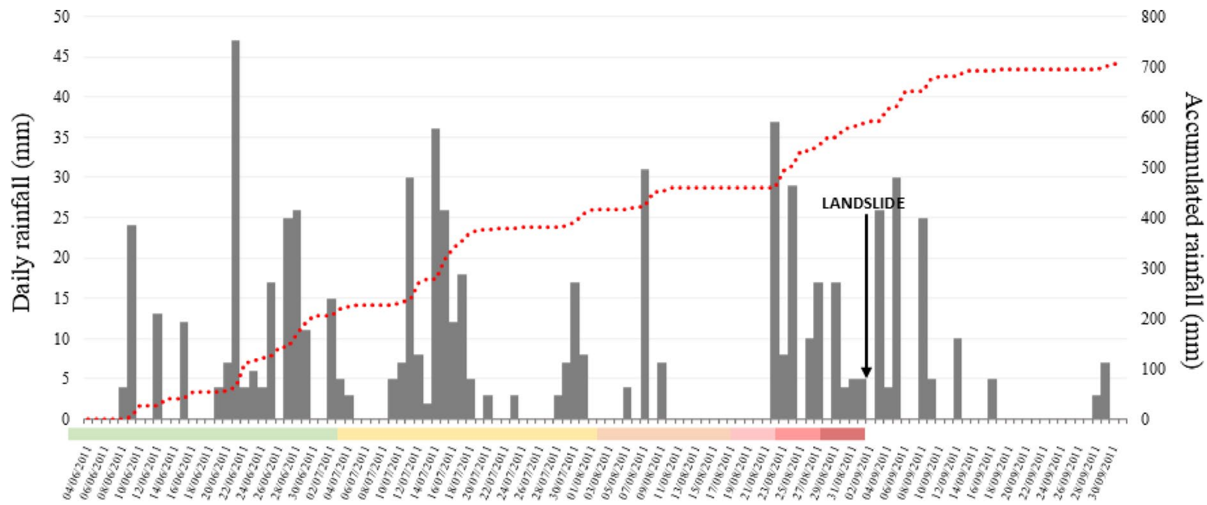

Fig. 7 Values of daily rainfall and accumulated rainfall associated with the landslide event (the colors of X correspond to those used in the table above)

Table 1 Accumulated rainfall during the 90 days before the landslide in Santiago Mitlatongo in September 2011.

Antecedent accumulated rainfall (0-90 days)			
Period	# of days	Precipitation (mm)	Accumulated precipitation (mm)
2011/06/03 -2011/07/ 03	90	219	219
2011/07/03 - 2011/08/02	60	198	417
2011/08/02 - 2011/08/17	30	42	459
2011/08/17 - 2011/08/22	15	0	459
2011/08/22 - 2011/08/27	10	84	543
2011/08/27 - 2011/09/01	5	43	586

1), total rainfall reached 129 mm (Table 1), exceeding the average precipitation for the entire month of August (118 mm) (CONAGUA, 2020).

The calculation of total rainfall accumulated over the previous 90 days indicates that it reached 586 mm (Table 1), while the total average rainfall for June, July, and August is 382 mm. In 2011, rainfall during this period (June-August) increased by 53% (CONAGUA, 2020).

Additionally, the historical record of this station indicates a trend of increasing annual rainfall, noticeable around 2010. The average annual precipitation during the period from 1981 to 2010 registered 685.8 mm, while the same parameter considering the period from 1983 to 2017 rises to 762.7 mm. When examining the average for the period from 2011 to 2017, the annual precipitation value increases to 1004.2 mm. Although the above value does not meet the minimum period defined to determine the existence of a change in precipitation patterns (30 years), a pattern of increase in total annual precipitation in the area is present.

The pluviometric analysis suggests that precipitation levels in the region have shown a sustained increase in recent decades. Although Mann-Kendall's analysis for this time period indicates an increasing trend in annual precipitation (S= 216, Var= 148736), values of Z statistic showed a value of 0.55 at a 95% confidence level, indicating no statistically significant trend. As for the detailed analysis of the conditions prior to the event, data indicate that the large amount of precipitation accumulated during the previous 10 days, in confluence with an increase in the average rainfall for that year, generated a scenario of increased soil moisture and slope instability that triggered the mass movement in the study area.

Geophysical studies prior to this work defined Mitlatongo as a complex landslide due to the occurrence of various types of movements within it. The mass wasting process is not uniform along its nearly three-kilometer length. On the one hand, in the northern sector of the unwashed tongue, where the head and rupture zone are located, there was a rockfall from the top of Peña Colorada hill. On the other hand, there is an apparent disagreement in the typology of the slip because Dominguez and Reyes (2012) define it as a translational type, while Gonzalez and Lopez (2016) classify it as a rotational type. Our analysis confirms that both processes occurred.

The geomorphological analysis indicates that the dynamics of the mass movement were influenced by pre-existing conditions and triggering factors. The presence of a fracture in the head zone since 1995 suggests that the valley has been undergoing instability processes for decades. Differences in the morphology and displacement of the units indicate that sliding did not occur homogeneously. In the eastern section, the material moved as a translational flow, while in the western section, the rotational movement originated a stepped topography with terraces and subsidence. The transformation of the relief resulted in the appearance of new bodies of water and the alteration of the water network prior to the event (Fig. 8).

Fig. 8 Water body developed after the 2011 landslide. February 2021

The management of the Santiago Mitlatongo disaster highlights the structural challenges in governmental responses to large-scale socio-environmental crises. While the first actions focused on the provision of immediate humanitarian aid, the lack of a comprehensive reconstruction and effective relocation plan prolonged the vulnerability of the inhabitants. The investment of 275.7 million pesos (approximately 22.2 million US dollars) for the resettlement of families and basic infrastructure was insufficient and marked by execution flaws and a lack of transparency, leaving the community in even more precarious conditions (Carrera Pineda, 2021; Redacción Imparcial, 2024). Furthermore, the lack of an official record on the progress of relocation reflects institutional negligence in accountability and public policy monitoring. The crisis not only persists in material terms but has led to additional social problems, such as violence and insecurity, as evidenced by recent episodes of crime in the area (Aguilar, 2024). This emphasizes the necessity of implementing more efficient governance mechanisms, with thorough oversight of reconstruction resources and a focus on community resilience.

Beyond institutional deficiencies in disaster management, it is crucial to understand the underlying causes of Mitlatongo's vulnerability from a geohistorical perspective. This allowed us to demonstrate how the geomorphological characteristics of the terrain, combined with historical processes such as intensive agriculture and deforestation due to overgrazing, have increased susceptibility to mass wasting processes. Furthermore, the current climatic context, where more intense and frequent rainfall aggravates the instability of a landscape already prone to these events due to its rugged topography and fragile geological conditions. Additionally, it is crucial to consider the historical responses of communities that have developed risk adaptation strategies since pre-Hispanic times, such as *lama-bordos* and various soil management techniques. Thus, the geohistorical perspective offers a comprehensive understanding of natural disasters as complex phenomena, highlighting the interaction between nature and culture in shaping vulnerability and generating mitigation and adaptation strategies.

Discussion

Situated geohistorical perspective and landscape transformation

Landslides in Latin America that affect the population cannot be understood solely as physical phenomena, but rather as socio-natural and historical processes, shaped by prolonged interactions between the environment, the economy, and territorial organization (Oliva et al., 2011; Acuña et al., 2021; Alcántara-Ayala & Sassa, 2023). In this framework, our work in Mitlatongo is framed within a situated epistemology of disaster (sensu Tironi et al., 2022), understanding the landscape from its physical-geographical dimension and as a result of local experience, colonial legacies, and the historical perspective for confronting natural disasters.

Thus, Mitlatongo is not presented merely as the territory affected by a large landslide, but as an unknown and transforming geography. It now appears as a newly formed and previously unmapped landscape. More than a decade after the 2011 landslide, this Mixtec valley has become a natural laboratory where the formation of new landforms, the reconfiguration of the drainage network, and the emergence of permanent bodies of water can be observed. These changes have led, for example, to the arrival of previously unrecorded bird species and the adaptation of farmers to the new soil conditions through the relocation of plots and the creation of agricultural terraces.

As in the work of Oliva et al. (2011), Mitlatongo can be categorized as a marginal territory due primarily to its weak institutional planning and geographic isolation. The valley's physical and administrative remoteness has resulted in insufficient management of both disaster prevention and response. This pattern is echoed in rural communities throughout the Global South (Tironi et al., 2022).

More than a decade on, the Mitlatongo landslide remains a current issue, as the disaster's consequences persist for the affected population: precarious housing and services in the relocation area, loss of agricultural land and livelihoods, community disruption and emotional and cultural damage, population aging, youth migration, and increased dependence on external support (remittances and government assistance). The need for risk management and monitoring demonstrates that there are still ample opportunities for improvement in land-use planning and management, and consequently, in the institutional actions of the region and the country.

Geomorphological complexity of the Mitlatongo landslide

The highly detailed geomorphological map confirmed that the landslide's complexity is greater than suggested in previous studies. Based on the results presented in sect. "Discussion", we identified the coexistence of a rotational and a translational landslide within the same event. This reinforces the argument put forth by Borja & Alcántara (2004) when they highlighted that the interaction between morphology, land use, and hydrological processes generates more heterogeneous instability patterns than theoretical models suggest.

This morphodynamic contrast allows us to understand the sequential evolution of the disaster and confirms that different mechanisms interact within a single event. Identifying both types of movement offers clues for interpreting its potential reactivation and the magnitude of the associated impacts (sensu Alcántara-Ayala & Sassa, 2023). In this way, the geomorphological map will serve as a baseline for future multi-temporal comparisons. The detailed mapping carried out confirmed that the displaced mass continues to change, justifying the need for continued monitoring of the valley.

The results of this study open the possibility of future research focused on: 1. Monitoring geomorphological evolution and post-event erosion; 2. Identifying new ecological indicators (such as the previously mentioned case of birds). 3. Evaluating the socio-economic and cultural resilience of the displaced population, and 4. Replicate this geohistorical approach in other regions of the Mixteca or Latin America affected by mass movements.

Conclusions

This study presents the first high-resolution geomorphological reconstruction of the 2011 Mitlatongo landslide, revealing it as a complex rotational–translational movement extending nearly three kilometers. By integrating geological structures, drone photogrammetry, historical aerial imagery, and rainfall analyses, we identified the long-standing instability of the valley and clarified the sequence of processes that culminated in the failure. The results confirm that the landslide was triggered by prolonged antecedent rainfall, amplified by the wedge-shaped structural configuration between the Tres Lagunas–Santa Cruz fault and the Pueblo Viejo syncline.

Methodologically, this research demonstrates the value of combining geospatial technologies with geohistorical evidence, offering a replicable approach for analyzing large landslides in poorly documented regions of the Global South. Scientifically, the study advances understanding of how structural geology and cumulative rainfall interact to condition catastrophic slope failures. Socially, the findings highlight the persistent vulnerabilities of Mitlatongo's displaced population, emphasizing the need for institutional strengthening, continuous monitoring, and the incorporation of geomorphological evidence into territorial planning and mitigation strategies in remote rural areas.

Overall, the study contributes a robust geomorphological baseline that can inform future hazard assessments and support more effective, evidence-based decision-making for risk reduction in structurally complex mountainous landscapes.

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