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ORIGINAL ARTICLE

Xitle Volcano Geoheritage, Mexico City: Raising Awareness of Natural Hazards and Environmental Sustainability in Active Volcanic Areas

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Abstract
The conservation of geosites in a region can foster its sustainability and develop geotourism. These geosites provide geoeducation, raise people's awareness on natural hazards, and increase their resilience. Low-income cities located in tectonically active areas combine high geohazards with high vulnerability and low sustainability. Geosites in these cities should be a tool to decrease people's vulnerability and foster sustainable development. Mexico City is an ideal case study for its environmental and social issues and its setting in an active continental volcanic arc. The 1700-year-old Xitle volcano, located in the city's SW corner, is a small scoria cone that erupted once, feeding an extensive lava field on which > 600,000 people now live. The lavas are very well exposed due to thin soils and extensive quarrying. The Xitle lavas covered the first urban center in the Mexico basin, except for the main pyramid that has become a major archeological site. The cone and lavas have significant geodiversity, sustaining a unique and biodiverse ecosystem. The country's largest university preserves the lavas in an ecological reserve. We describe four exceptional geosites, assess their values, and discuss their relevance for addressing issues such as nature preservation, environmental sustainability, social inequalities, and natural hazards. The Xitle volcano provides a wide range of benefits for the city that are nonetheless unknown to its inhabitants. We describe ongoing initiatives to disseminate such information, such as the Geopedregal site, and propose ways that this heritage could be further protected and used by the city in a sustainable way.

Keywords Volcanic geosites · Geoeducation · Geodiversity · Geohazards · Sustainability

Introduction

The preservation, recuperation, and valuing of natural sites in cities is a way to promote nature conservation, environmental sustainability, and human well-being (e.g., Hough 2004; Jim 2004; van den Berg et al. 2010). The importance of biological elements for attaining these benefits is widely recognized, yet geological elements (such as rocks, landforms, fossils, etc.) are generally not or hardly considered in environmental policies and urban planning (e.g., Boothroyd and McHenry 2019; Gray 2013; Brilha et al. 2018; Gray 2018; Gordon et al. 2018). Accordingly, protected green spaces are relatively common in cities (e.g., Jim 2013; Zambrano et al. 2019), whereas analogous places for rocks and landforms are rare (Portal and Kerguillec 2018). Construction works continuously expose new outcrops, but these are generally viewed as unaesthetic and a source of danger through falling blocks; hence, exposures are frequently destroyed or covered, losing their potential value (Reynard et al. 2017; Vereb et al. 2020). In the long term, the original topography and landscape is altered significantly, alienating people from their local geology, territory, and natural setting (e.g., Reynard et al. 2017; Ticar et al. 2017; Clivaz and Reynard 2018), with potentially disastrous consequences for their environmental well-being and their awareness of natural hazards.

Geoparks are good examples of how the conservation of remarkable geological elements of a territory (i.e., geoheritage) can be used through education and tourism to

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promote sustainability (e.g., McKeever and Zouros 2005). These programs are based on the identification of sites that contain geological elements either with high scientific value (geosites) or with limited scientific value but high touristic and educational potential (geodiversity sites) (Brilha 2016). The conservation and valuing of geosites in cities could help them reach greater environmental sustainability, increase human wellness, as well as develop new sources of revenue through geotourism (Rodrigues et al. 2011; Górska-Zabielska and Zabielski 2017; Ticar et al. 2017; Reynard et al. 2017). Urban geosites can also enhance knowledge and people's perception of the relationship between urban development, culture, and natural processes (Del Monte et al. 2013; Pica et al. 2016, 2017; Reynard et al. 2017). Such initiatives are particularly relevant in areas with high georisks, because they provide geoeducation and strengthen local communities, improving social awareness and resilience to hazards and reducing disaster risk (Eiser et al. 2012; Fassoulas et al. 2018; Pavlova 2019; Petrosino et al. 2019). Identifying geosites in cities of developing countries that are located in tectonically active areas (i.e., close to tectonic plate edges) is crucial because these cities combine multiple geohazards (such as earthquakes, volcanoes, landslides, flooding) with high vulnerability and low sustainability due to a wide range of socio-economic, educational, and political issues (e.g., Hardoy et al. 2013). The metropolis of Mexico City is one of the largest urban areas in the world (> 20.9 million inhabitants, INEGI 2010), with infamous environmental problems (e.g., Schteingart 1989). Because of its location in a lake basin at the center of an active volcanic arc, the city is exposed to numerous natural hazards including earthquakes, volcanic eruptions, water shortages, subsidence, landslides, and flooding (e.g., Siebe and Macías 2006; Aragón-Durand 2007; Mancebo 2007; Ortiz-Zamora and Ortega-Guerrero 2010). Although these hazards affect the society as a whole, poor people living in the city's outskirts are particularly vulnerable (e.g., Mancebo 2007; Eakin et al. 2016).

Recent events such as the series of large earthquakes in 2017 have shown that most people in Mexico City lack basic knowledge on geology and natural processes in general, and distrust official information. In contrast, they are particularly susceptible to influence from deformed, inaccurate, or false information (*fake news*) diffused through the Internet, which decreases their ability to understand scientifically validated information and take appropriate measures for their own protection. Scientists lack time to transmit their knowledge at the scale and constancy needed, and the medias often distort their message for their convenience. In this context, geosites could be a tool to improve both sustainability and awareness on geohazards by preserving natural spaces and facilitating continual communication between the science community and society, improving geoeducation and reducing the risk of disasters.

The general aim of this paper is to demonstrate the wide range of benefits associated with preserving and developing urban geosites with the remarkable case of the Xitle volcano in SW Mexico City. Xitle is a young volcano that formed on the edge of the Mexico basin by a single, uninterrupted eruption less than 1700 years ago (Siebe 2000). Its eruption produced a large lava field that hosts the last remaining natural sites in the southern part of Mexico City, as well as the central campus of Mexico's national university that is a major World Heritage cultural site (Pezzoli 2000; Cano-Santana et al. 2006). Palacio and Guilbaud et al. (2015) identified nine geosites related to the volcano that have high geological, archaeological, cultural, and educational relevance. In this paper, we present a more complete, holistic assessment of the geoheritage value of this volcano, by emphasizing its relevance to conservation, education, and research on the global Earth system, including anthropogenic activity. We select and describe in detail four geosites that should be considered a priority for conservation and promotion due to their high values of representativeness, integrity, association with additional values (environmental, archaeological, etc.), observation conditions, and didactic potential. We also name other sites that have lower scientific value but which could be used for local outreach and touristic activities. All these sites are threatened with serious damage due to the densification of the city and the need of new land for housing and educational infrastructure (Pezzoli 2000; Cano-Santana et al. 2006; Aguilar and Santos 2011; Pérez-Galicia and Pérez-Campuzano 2015). The specific goal of this study is to provide the necessary elements to the university and the local authorities to plan specific actions in order to guarantee the preservation and popularization of the Xitle geoheritage, which in turn would help protect the city itself from natural hazards.

The Xitle Volcano

Xitle volcano consists of a small scoria cone (140 m high, 500 m wide) and a large lava field (ca. 80 km^2) that were produced by a single basaltic eruption less than 1670 years ago (Delgado et al. 1998; Siebe 2000). The volcano erupted at 3000 m asl, on the northern flank of the Sierra Chichinautzin mountain range that borders the south of Mexico Basin (Fig. 1). After an initial explosive phase, the volcano effused lavas that flowed down into, and invaded the southwest part of the Mexico basin, burying most of a pre-Hispanic city (Cuicuilco) and reaching the shores of the ancient, now mostly drained, Xochimilco and Texcoco lakes at ca. 2250 m asl, 12 km from source. The lava field is complex and consists of multiple units indicating a pulsing effusive activity punctuated by minor

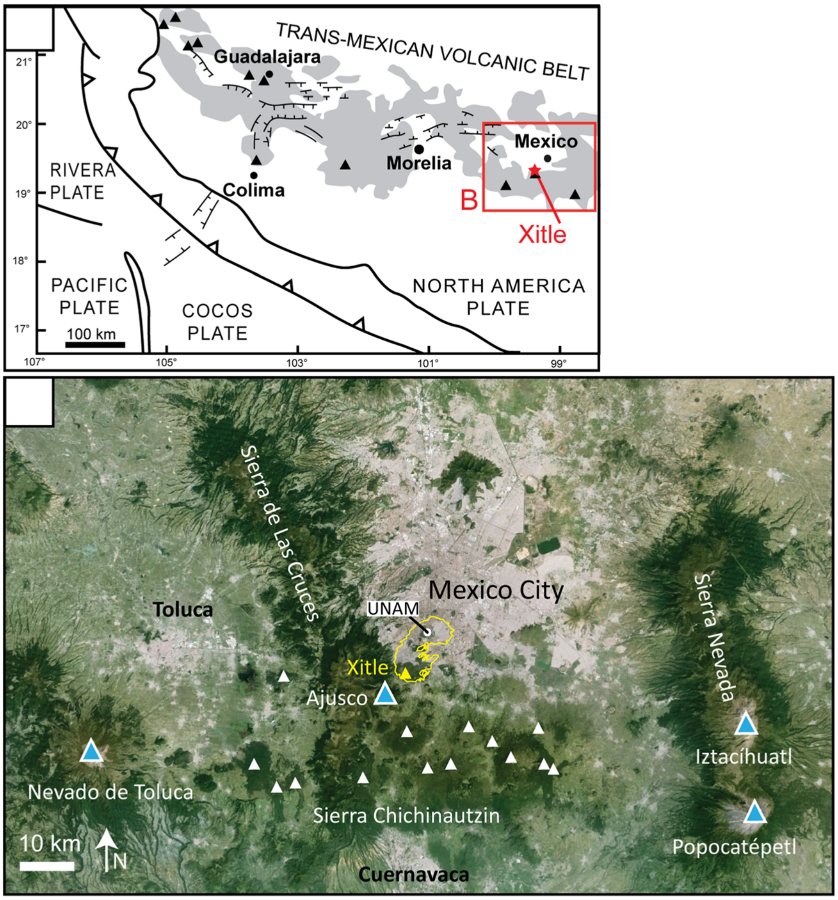


Fig. 1 a Localization of the Xitle volcano and Mexico City in the Trans-Mexican Volcanic Belt and associated arc-type tectonic system. Dark filled triangles indicate mayor stratovolcanoes along the belt. Black filled points indicate main cities with millions of inhabitants. Note that most of these are located in the volcanic belt and hence at risks from new and ongoing eruptions. b Localization of Xitle volcano (yellow triangle) and Xitle lava field (yellow polygon) including the UNAM campus, in the SW corner of the Mexico Basin host to Mexico City. White triangles are volcanoes of the Sierra Chichinautzin formed during the last 15,000 years. Blue and white triangles are stratovolcanoes. Popocatépetl is in eruption since 1994, while the Nevado de Toluca last erupted 10,000 years ago. Ajusco is extinct

explosive phases. The large volume erupted (> 1 km^3) suggests that the eruption lasted a decade or more. The lavas form barren, rocky land with irregular topography that was mostly left un-populated, until the central campus of the National University of Mexico (UNAM) was built in 1948–1952 on the far end of the flow (Fig. 2a, b; Carrillo-Trueba 1995; Salas Portugal 2006). At about the same time, the Jardines del Pedregal (gardens of the rocky place), an exclusive residential area just west of UNAM, was constructed under the guidance of world-renowned architects and artists (e.g., Rivera 1952; Pérez-Méndez 2007). The urbanization of the lava continued southwards and towards the volcano, with the construction of housing and infrastructure for the Olympic games of 1968 (Fig. 2c), followed by extensive residential areas and commercial centers in the early 1970s (Fig. 2d). By now, the city has incorporated almost the entire lava field, except for a few patches, which are under high stress (Cano-Santana et al. 2006). The largest and best conserved of these patches is the Reserva Ecológical de San Ángel or REPSA, an ecological reserve with a core zone of 171 ha and a buffer zone of 66 ha that was created in 1983 inside UNAM (http://www.repsa.unam.mx; Zambrano et al. 2016). About 660,000 people currently live on the lava field (Hernández-Robles 2019), most of them without knowing that they sleep on a bed of lava.

Characterization of the Xitle Volcano Area: Geological, Environmental, and Additional Values

Geological Processes and Volcanology

Xitle volcano is located in an area of intense and highly active volcanic, tectonic, and sedimentary processes (Fig. 1). It is part of the Quaternary Sierra Chichinautzin volcanic field, which consists of more than 200 small volcanic edifices, most of them scoria cones and lavas (e.g., Bloomfield 1975; Martín del Pozzo 1982; Márquez et al. 1999; Siebe 2000; Arce et al. 2013). This volcanic field forms the central part of the active Trans-Mexican volcanic belt, a wide band that crosses Mexico east-west and includes stratovolcanoes, vast fields of small, monogenetic volcanoes, and some calderas (Fig. 1). The axial part of the belt is affected by extensional forces that created a series of high-altitude (> 2000 m asl) tectonic basins, including the Mexico basin where the city is located (Fig.

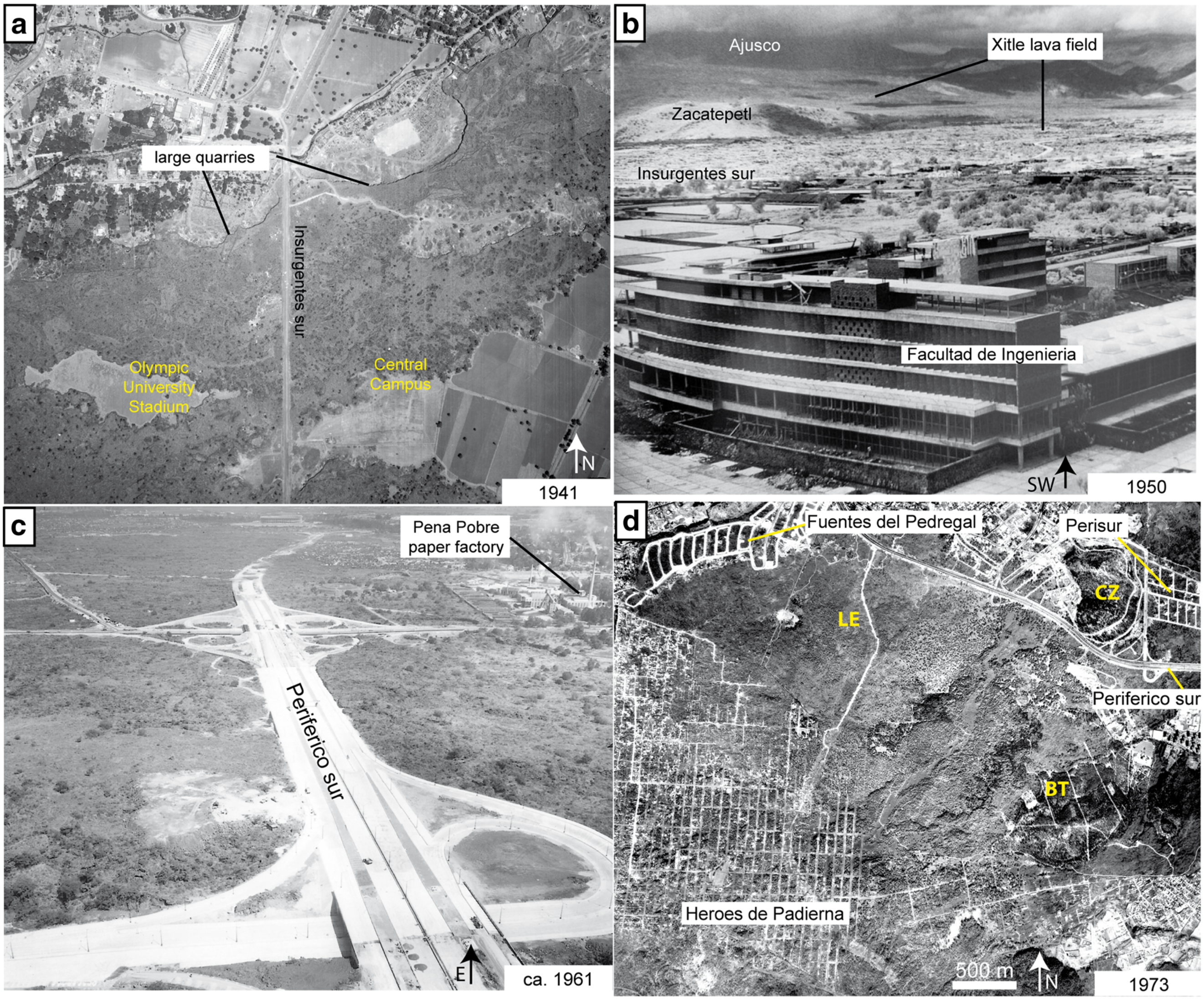


Fig. 2 a Vertical aerial photo of the present location of the central part of the UNAM campus in 1941 (FICA foundation). The location of the agricultural fields where the Olympic University stadium and the Central Campus were constructed few years later is indicated. Note also the concave shape of large quarries into the lavas that are now urbanized. The entire area is virtually unrecognizable in today's photographs. b Oblique aerial photo of the first university building constructed over the lava field (taken from Salas Portugal 2006). c Oblique aerial photo of the southern peripheric road of Mexico City (Periferico sur), just after its construction on the lavas in 1961 (provided by A. Lentz). d Vertical aerial photo of the lava field to the south of the Periferico sur in 1973. Note the road tracks of an exclusive residential area (Fuentes del Pedregal) and a mall (Perisur) in the northern part, and a more extensive popular area (Heroes de Padierna) to the southeast. The area is now entirely urbanized, except for few remaining patches including the Los Encinos area (LE), the summit of Cerro Zacatépetl hill (CZ), and the Bosque de Tlalpan (BT)

1). The basins are filled by lacustrine and volcaniclastic sediments and were occupied by shallow endorheic lakes that have largely disappeared due to anthropogenic activity. The Xitle volcano is a strong marker of this highly dynamic setting, as its cone was built on the border of the graben and its lava interacted with one of the preexisting lakes in the basin.

In terms of volcanology, Xitle is a fine example of a basaltic scoria cone and associated lavas, which are the most common volcanic structures on Earth (Fig. 3c; Wood 1980). This type of volcano is commonly called monogenetic, as they are formed by single (mono) eruptions with one cause (genetic). While scoria cones are abundant along the Trans-Mexican volcanic belt, basalts are atypical in subduction settings, and especially so the alkaline, Ocean Island Basalt-type erupted at Xitle. This drives strong interest on this particular volcano for geochemical studies on the source of magmatism in this region (e.g., Straub et al. 2008).

Both the surface and the interior of Xitle lavas are exceptionally well exposed, because soils are barely formed, due to the young age of the basaltic lava that is hard to erode in the arid climate, and because of abundant quarrying due to the

Fig. 3 a Detail of a painting on the facade of the town hall building of Tlalpán featuring pre-Hispanic people fleeing the Xitle eruption. b Photograph of a vertical cut into a sheet lobe along the Insurgentes avenue in UNAM. Men point to a vertical line of holes drilled for paleomagnetism studies. c Photograph of the Xitle cone and proximal lavas covered by a pine tree forest, from the south. d Photograph of the vegetated lava flow preserved in the Cuicuilco archaeological site. Note the Xitle cone and Ajusco stratovolcano in the distance. e Photograph of the Anahuacalli museum built by Diego Rivera to expose its collection of archaeologic pieces. It is made entirely by stones from the Xitle lava and preserves a patch of the lava field around it

expansion of Mexico City. Excavations have taken different forms with time. Large quarries made to extract building stones were most prominent prior to the urbanization of the area. Important road cuts were made when large avenues (Insurgentes sur, Periferico sur) were constructed, and now excavation is restricted to small private areas, with the aim to construct underground parking areas and to anchor structures against earthquakes. Most of these excavations and any resulting exposures of the internal structure of the lava are however covered up when the work ends, which reduces the number of long-lasting exposures that can be of use for research or education. Early on, the outcrops resulting from the active quarrying have motivated the pioneering works of Waitz and Wittich (1910), Wittich (1919), Schmitter (1953), and Badilla-Cruz (1977), and the more recent works of George Walker, the father of modern volcanology, who revisited the early interpretations (Walker 1993, 2009). The many sections cut though the lavas have also permitted numerous studies on the internal magnetic properties of basaltic lava flows (e.g., Cañon-Tapia et al. 1995, 1996). The quarrying is an example of how geoheritage can be promoted by extraction, *if* the exposures are accessible and preserved.

Volcanic and Seismic Hazards

Due to its tectonic setting, Mexico City is surrounded by many young, active volcanoes and hence exposed to significant volcanic hazards (Fig. 1, Siebe and Macías 2006). The most obvious source of hazards is the Popocatépetl stratovolcano, which has been in eruption since 1994 and the ash of which occasionally reaches the city. However, the dormant Nevado de Toluca volcano located 50 km west of the city and not visible from it (Fig. 1) has deposited thick pumice layers in the Mexico basin, and is hence also a potential hazard that is unknown to city dwellers. Another potential, yet unknown hazard is that of the formation of a new monogenetic volcano within the Sierra Chichinautzin volcanic field. This is also a probable impact even on Mexico City, as 14 such volcanoes (including Xitle) have erupted during the last 15,000 years (Fig. 1, Siebe et al. 2004a, 2005; Arce et al. 2015; Guilbaud et al. 2015). These volcanoes are poorly known by the public, despite the famous eruption of the Paricutin volcano in Michoacán in 1943–1952 (Luhr and Simkin 1993), being a classic Mexican example. Xitle volcano is the most recent example of such type of volcano near the city, its products are well-exposed, and there is clear evidence for its direct impact on human settlement (see below). Hence, it is key to study and educate about hazards linked to monogenetic eruptions in this area.

About seismic hazards, during the past centuries, Mexico City has been affected by large magnitude earthquakes that have caused serious material damage and loss of life (e.g., Campillo et al. 1989; Singh et al. 2018). During those, the uneven distribution of the damage revealed the crucial role of the ground firmness, the so-called site effect, on the intensity and magnitude of the ground shaking. This then resulted in the zoning of the Mexico basin in terms of seismic hazards and associated construction rules (e.g., Campillo et al. 1989; Flores-Estrella et al. 2007). By being firm and located on the edge of the basin, Xitle lavas are a safe area to live and work, and thus a testimony of the natural factors affecting seismic hazards. It is noteworthy that the UNAM campus in the city hosts the Servicio Sismológico Nacional (SSN) that is in charge of surveying the seismic activity in the whole country and informing authorities and population (www.ssn.unam.mx). It is hence a key actor for the mitigation of seismic risks.

Hydrogeology, Water Resources, and Flood Hazards

Typical for young basaltic lavas, the Xitle lavas have high hydraulic connectivity, which means that water infiltrates quickly and percolates in the porous rock, forming aquifers (Peterson 1972). For their specific topographic setting, the Xitle lavas act as a natural conductor of rainwater from more humid, higher parts of the Sierra Chichinautzin, to the drier, lower-elevation basin where springs occur (e.g., the Pumas quarry site, see pictures and descriptions below). They also serve as a buffer to floods that occur every summer rainy season in the basin, because the lavas soak up water. Despite the shortage of water resources in the basin and common interference of construction works in them, the aquifer in the Xitle lava is poorly studied and strongly impacted by anthropic pollution (Canteiro et al. 2019). Its existence should be valued, and recognized as a means to increase the city's sustainability.

Biodiversity, Ecology, and Environment

Young basaltic lavas are a very peculiar substrate on which plant colonization is slow and selective, hence fostering the formation of a specific ecosystem (e.g., Del Moral and Grishin 1999). The vegetation of the Xitle lava field has been mapped by Carrillo-Trueba (1995), revealing a diverse plant pattern that varies mostly with altitude. While high-standing areas (> 2500 m asl) are dominated by forests of pine tree, oak, and fir (e.g., the vent area, Fig. 3c), low-altitude areas (< 2500 m asl) are mainly covered by a xeric scrub dominated by *Pittocaulon praecox* that is native to Central Mexico (Rzedowski 1954) (e.g., the distal lavas, Fig. 3d). The *Pittocaulon praecox* is a peculiar bush locally named palo loco or mad branch, in Spanish, because it flowers in the dry season when the rest of the vegetation is almost completely dry. This vegetation type is associated with a high biodiversity, having almost 1820 species of all taxonomic groups recognized, 32 of which are under protection by Mexican laws and 54 of which are endemic to Mexico (e.g., Lot and Cano-Santana 2009; Zambrano et al. 2016). The specifics of this ecosystem strongly rely on the peculiar microtopography of the lava, which yields variable conditions of temperature, humidity, light, and organic soil depth, promoting many biological adaptations in a climate alternating between clear dry and rainy seasons (e.g., Castellanos-Vargas et al. 2017).

Archaeology and Radiometric Dating

Xitle has a profound significance for archaeology, as its eruption destroyed the first large urban center of the Mexico basin (Cuicuilco). The abandonment of this site as a possible consequence of the eruption coincides with the expansion of the city of Teotihuacan, located further north, that became one of the largest urban areas in the world in the Classic period, AD 350–650 (e.g., Cummings 1926; González et al. 2000; Siebe 2000). Although it is yet to be validated, as there are no historical accounts and radiometric dates for the eruption are variable (see discussion in Siebe 2000), the eruption is pictured as responsible for a major human disaster, as portrayed in paintings located in a small museum in the Cuicuilco archaeological site and on the town hall of Tlalpán, a district of Mexico City that was originally a village at the edge of the city (Fig. 3a).

Due to its archaeological significance and excellent exposure, the Xitle lava is the most dated in Mexico, both by radiocarbon and paleomagnetic methods (e.g., Siebe 2000; Urrutia-Fucugauchi et al. 2016). The first radiocarbon age that was acquired for this eruption (2422 ± 250 years BP) was one of the first ages obtained by the radiocarbon method worldwide (Arnold and Libby 1951), which shows its importance for the development of a key dating method for the Holocene and Late Pleistocene. Series of holes drilled in nearly every major vertical section in the lavas reflect also its extensive use for the paleomagnetism calibration that has a wide range of applications worldwide (Fig. 3b).

Arts and Aesthetics, Architecture, and Cultural Heritage

The Xitle lava has been the source of abundant creative work, which expresses its significance for the cultural identity of this area and makes it part of the intangible heritage. The peculiar landscape formed by the lavas (locally called Pedregal de San Ángel) has inspired many artists in the past, including painters like Diego Rivera, David Alfaro Siqueiros, Gerardo Murillo (Dr Atl) and Joaquin Clausell, photographers (Hugo Brehme and Armando Salas Portugal), sculptors (Federico Silva, Helena Escobedo, Mathias Goeritz, Francisco Soto), poets (e.g., Carlos Pellicer), and architects (Luis Baragan, Max Cetto house studio). It remains an inspiration for artists today such as Abraham Cruzvillegas, with his provocative wall of trash named Reconstrucción (2016), illustrators like Aslam Narvaez and Elvia Esparza, and many photographers who recognize the unique beauty of both the lava forms and biodiversity. Several monuments of the Ruta de la amistad (route of friendship), a series of 20 sculptures made by renowned artists in the southern part of Mexico City for the 1968 Olympic games, were strongly inspired by the lava outcrops on which they were built, and some of the artistic works remain placed where the lavas are nicely exposed (Camarena-Berruecos 2010). The natural ecosystem formed over the lava and preserved in the ecological reserve makes UNAM's main campus to be mentioned as the most beautiful university in Latin America, and has been described as "a green oasis in the middle of a megalopolis" (Krieger 2008).

As for architecture and cultural heritage, the Xitle lava has been used abundantly as building stone for its aesthetic value, resistance to erosion, and direct availability at construction sites. The rocks hence form part of the architectural heritage of the area and contribute to its identity inside the immense, multi-cultural megalopolis. In planning the exclusive Jardínes del Pedregal residential area that was constructed over the Xitle lava, Diego Rivera, probably Mexico's best known and most emblematic artist along with his wife Frida Kahlo, highlighted the benefits of the use of locally derived lava blocks that are valuable for their homogeneity, solidity, low cost, and beauty (Rivera 1952). The Anahuacalli museum that he built still hosts his collection of pre-Hispanic objects and is a clear demonstration of these precepts (Fig. 3e). These same ideas directed the planning of the central part of the UNAM campus, which is considered as one of the most important architectural works of the last century, and which was declared World Heritage site in 2007 (World Heritage Committee 2007). Another example is the house called casa del Indio in the Coyoacán district that was built mostly by lava, by a famous architect, Manuel Parra, for an emblematic Mexican actor (Emilio Fernández) and that can be visited. Besides these sites, the distinct light to dark grey microvesiculated Xitle stone is part of many buildings, walls, stairs, and platforms in the SW corner of Mexico City, which highly contributes to the aesthetics and sense of identity of this area of the city. Nevertheless, its use is declining, and efforts should be made to promote it in the construction of new buildings, in order to conserve the area's identity.

Description of the Geosites

Palacio and Guilbaud et al. (2015) identify and describe nine geosites in products from the Xitle volcano, six of them located within UNAM's ecological reserve. We revised this work, redefined the areas of interest, and describe below four sites that present the highest scientific, touristic, and educational values, and hence highest significance for valuing and conservation, and are here considered as primary geosites or *geosites sensus stricto* according to Brilha (2016). We also briefly refer to *other sites with similar scientific values* that generally have more limited size and poorer state of preservation but can have local cultural, educational, or ecological significance. These could be considered as geodiversity sites following Vereb et al. (2020). While Palacio and Guilbaud et al. (2015) focused on volcanological aspects, here we adopt a more holistic assessment and incorporate archaeological, historical, educational and biological,

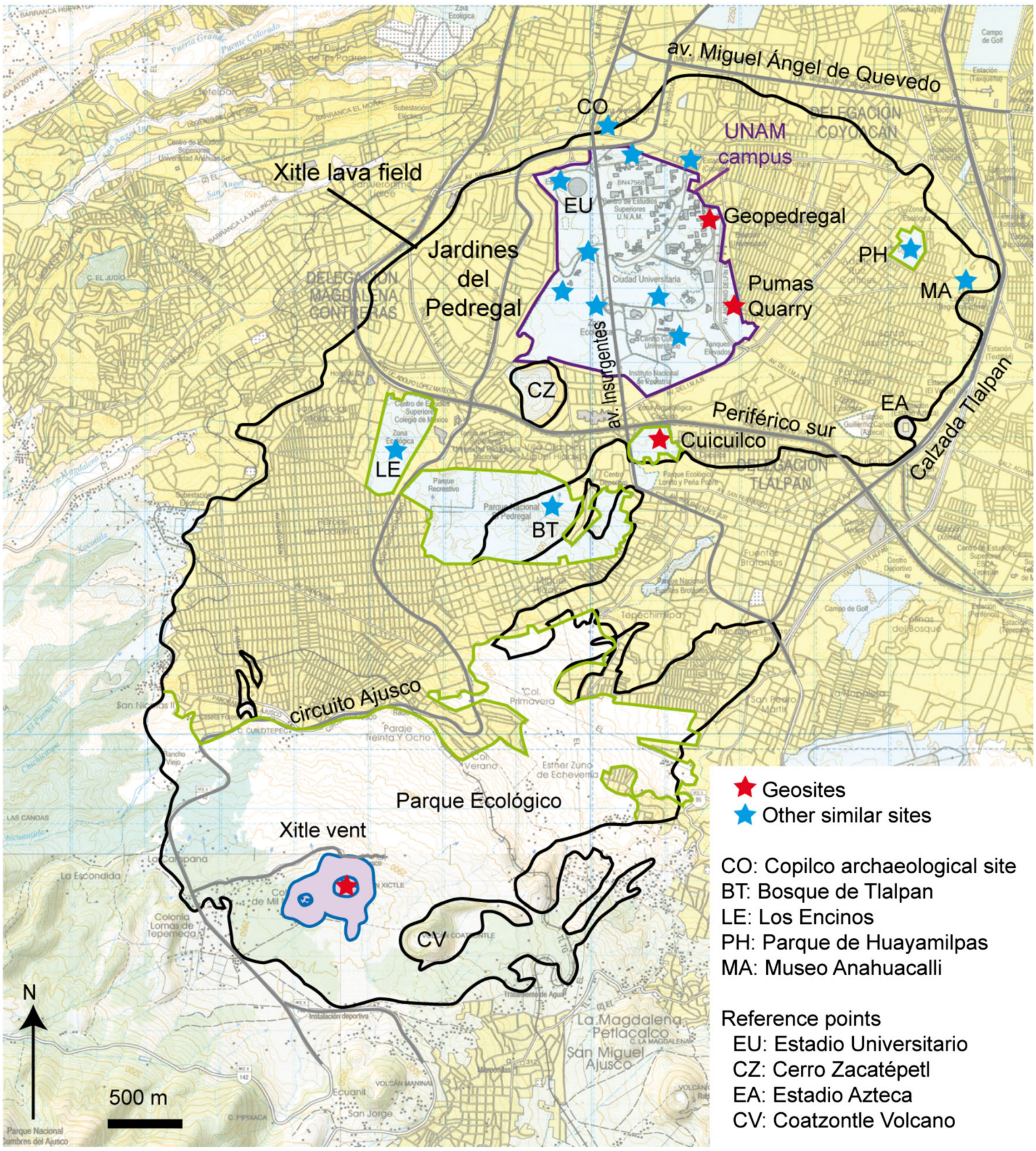


Fig. 4 General map of the Xitle cone and lava flow field with the location of important reference points in the city and the sites described in the text. Note that the topographic map used as background indicate in yellow the constructed areas, while "natural" areas are left in white. Most of these correspond to places where the lava surface and its vegetation can still be observed, although illegal settlements are commonly found and deteriorate the sites

ecological, and pedological considerations to highlight the multiple and diverse sources of interest of the sites and underline their importance for geoconservation and geoeducation. Descriptions are rather long and complete at the sites where these features had not been described before, to make a sound record and encourage further investigation. The sites are located on Fig. 4 for further reference. We present a quantitative assessment of the values of these geosites in the following section.

Xitle Vent Geosite

This site is located at high altitude, on the northern flank of the Sierra Chichinautzin range (Figs. 1 and 4). We first provide a short summary, and then describe the area in details, presenting maps of the volcanological elements (Fig. 5a, b) and the related vegetation pattern (Fig. 5c), and showing photographs of the main elements (Fig. 6). As developed below, this site has high geodiversity which is strongly and clearly linked with

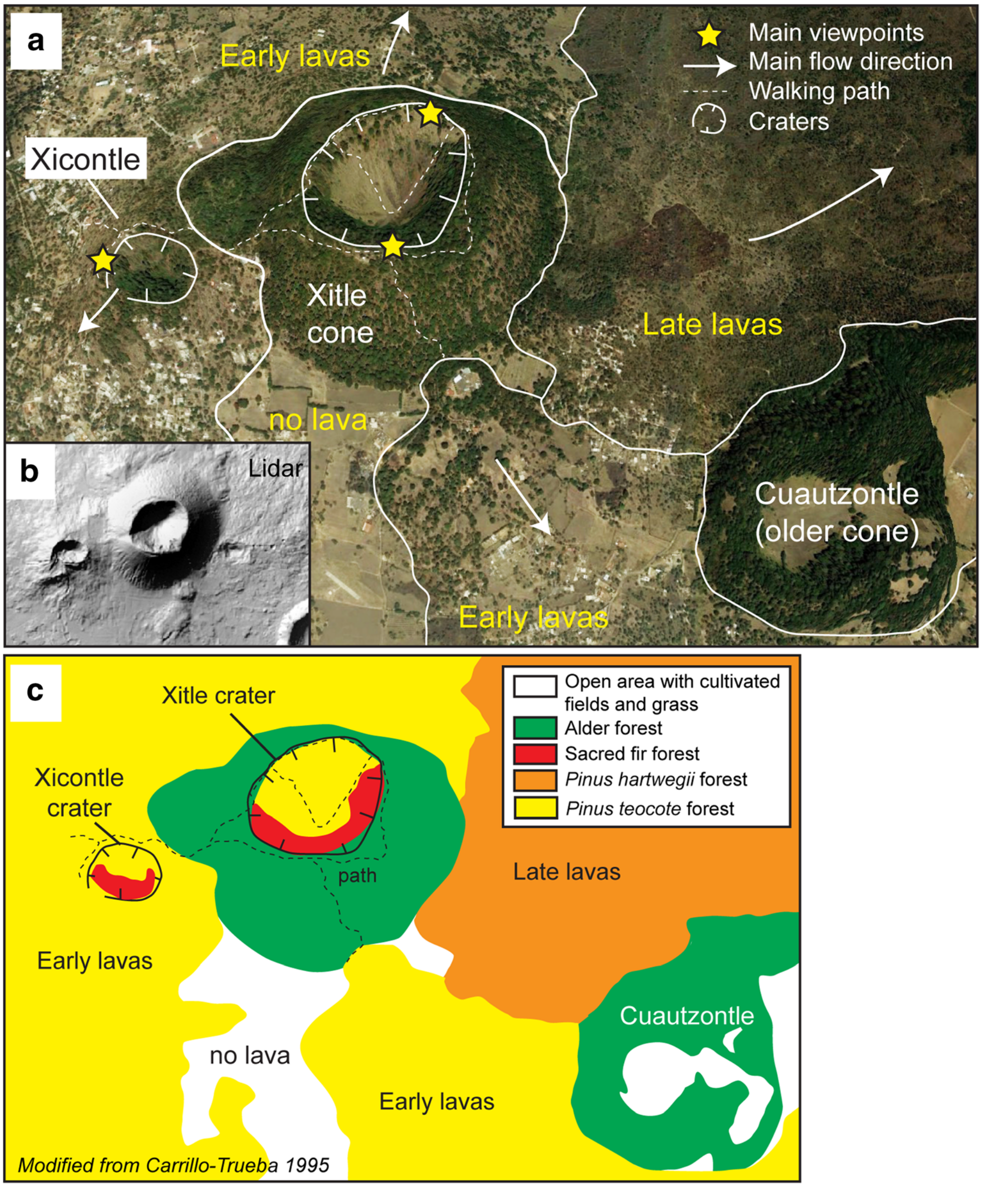


Fig. 5 Vent area geosite: maps. a Cartography of main volcanic elements along with the walking paths and location of early- and late-formed lavas on a slightly inclined view of satellite images draped over an elevation model from Google Earth. b Shaded relief from a 5-m resolution digital elevation model that shows clearly the shape and inner crater of the main scoria cone and the Xicontle spatter-lava cone. c Vegetation cover map modified from Carrillo-Trueba (1995) and drawn from satellite images and field observations. See the text for more explanation

elements of pedodiversity and biodiversity, of significant scientific and educational interest.

Summary This site contains typical, proximal products of Strombolian-style basaltic activity (the weakest form of explosive volcanic activity) that are particularly well preserved and exposed. The area also features a range in vegetation cover and dominant tree species that are correlated with variations in the parental material (lava, scoria or tephra) and the overlying developed soil, the orientation of the cones' slopes (slope aspect) that controls the amount of solar insulation and humidity, and with the variation in altitude that allows different rainfall and humidity regimes. The dominant tree species are either endemic to Mexico or to Central Mexico, which is of biological relevance because of their associations and also have importance for their educational value. The position of the main cone on an elevated plateau directly south of the city provides panoramic views of the Mexico basin and surrounding volcanoes that are both aesthetic and instructive. As for touristic values, this site is a pleasant, green area with low atmospheric contamination that is easily accessible by city dwellers. Numerous people go to this area in the weekends to enjoy small restaurants and outdoor activities such as horse riding, hiking, and mountain biking. The walking paths are easy and do not require specific equipment. For the cultural aspect, we have witnessed locals engaged in religious ceremonies that take place near the main crater, but this aspect needs to be investigated further in the future. Scientific values are described in more detail below, distinguishing between volcanological, biological, and pedological aspects.

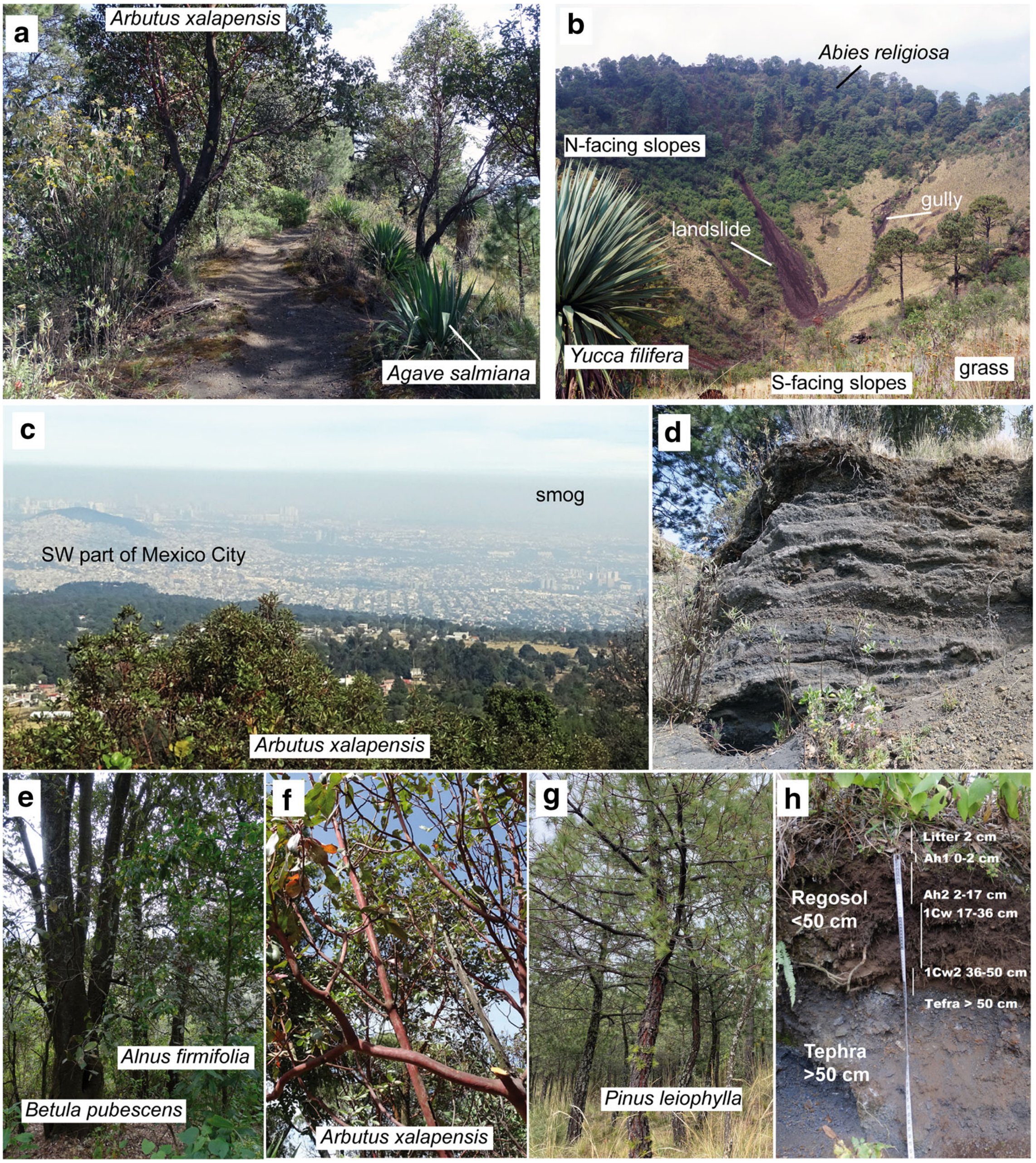


Fig. 6 Vent area geosite: pictures. a Photograph showing the path surrounding the crater rim of the Xitle cone on its west side and the associated vegetation pattern. b Photograph taken from the south part of the crater rim, looking north, showing the N- and S-facing crater slopes and their contrast in vegetation and erosional pattern. c Photograph on the view from the southern part of the Xitle crater rim looking N, showing the southern part of Mexico City covered by smog. d Photograph of a ca. 1-m deep exposure into the outermost layers of the Xitle cone that consist of layers of tephra, from ash to lapilli in size. e–g Photographs of important tree species on the Xitle cone. h Photograph of the soil section described in detail in Table 2 and in the text

Scientific Interests: Volcanology The vent area consists of a scoria cone (Xitle proper) and a spatter and lava cone (Xicontle) that are aligned in a broad east-west direction, suggesting a fissure (Fig. 5a, b). This type of "monogenetic" volcano is the most abundant on the planet, and its components are particularly well-preserved and well-exposed here. The alignment of the Xitle and Xicontle vents highlights the ascent of the magma driving the eruption along tectonic planes in the crust (faults), forming dikes that create a line of eruptive vents when intersecting the surface. The scoria cone has a deep internal crater (50 m) and relatively steep (ca. 30°) smooth outer slopes (Fig. 5b), which probably explain the name of Xitle that means belly button in the indigenous Nahuatl language. This morphology reflects the young age of the cone whose original aspects have not been significantly affected by weathering. Small paths allow the ascent of

Xicontle and Xitle and follow their crater rim (Fig. 6a), and at Xitle, descend to the bottom of the crater (Fig. 6b). The slopes of the scoria cone's crater have gullies and small-scale landslides made of loose, bomb-size scoria, indicative of erosion by colluvial transport that controls the morphological evolution of the crater (Fig. 6b). Viewpoints offer clear views of the crater interiors, the southern part of the Mexico Basin (commonly covered by smog), and Ajusco's northern slopes, that are important components of the general geological and geographical setting (Fig. 6c). On clear days, the Popocatepetl and Iztaccihuatl stratovolcanoes that border the Mexico Basin to the east can be seen. Cuts along the paths and gullies on the slopes expose the scoria cone interior that consists of an alternation of scoria and ash layers (Fig. 6d), as well as lava bombs and short flows. Such deposits are typical products of mildly explosive activity that occurs at basaltic cones. In contrast, Xicontle is made of a superposition of spatter layers and thin (< 1 m) lavas exposed in the crater, which are the products of lava fountaining that typically occur during weak explosive activity along fissures. The good exposure of these products of weak to mildly explosive basaltic volcanism represents an educational asset. Of additional interest in this area is a lava flow unit to the east of the main cone that has no tephra cover, indicating that it formed late, after the cone-forming explosions (Fig. 5a). These lavas host a system of caves (lava tubes) linked to collapse structures (skylights) and some channels. The lava tubes are important elements of basaltic lavas that strongly contribute to the large areas covered by these flows, due to being very well insulated (Keszthelyi 1995). They are exposed as empty, elongated cavities when their interior is drained, which probably occurred here at the end of the eruption. These interesting aspects of the volcano are worth further investigation given their relevance for understanding the recent, impactful volcanic activity close to Mexico City.

Pedology There are interesting links between the elements of geodiversity of the vent area, and other factors controlling the soil formation (relief, microclimate, and organisms). Variations in the topography in the vent area create some diversity in the soils. On the cone, soils are formed from recently deposited unconsolidated volcanic ash and are hence shallow, very stony, with incipient accumulation of organic matter and very weak structure, classifying as haplic Regosol, tephric, skeletic (humic) (Fig. 6h, Table 2, IUSS Working Group WRB 2015). They are also highly porous and allow root growth to depths of up to 70 cm. Soil depth and color vary with altitude, slope angle, and slope orientation. Soils are deeper at higher altitude because of an increase in the amount and size of the deposited unconsolidated tephra material. Steeper slopes have lower material stability, lower accumulation and hence less soil depth. Slope orientated to the north causes shady, less-exposed areas to be more humid and have more trees and hence be more organic (darker colored soils). In contrast, slopes with southern, sun exposure are drier and have light-colored soils (Porta et al. 2019). Hence, the south-facing hillside inside the crater with a 35° slope, has low material accumulation, greater sun exposure, less humidity and a vegetation of grass and few trees. The result is a shallow, light-colored soil, because of low organic matter accumulation.

Biology The vegetation in the vent area follows a pattern that matches the distribution of the volcanological elements (cone, crater, lava), each of them presenting distinct soil types and microenvironments due to variations in altitude and sun exposure (Fig. 5c). Our field observations in February 2020 are generally consistent with the map of Carrillo-Trueba (1995) although we noted some differences. The outer-slopes of the main cone that were mapped as an alder forest by Carrillo-Trueba (1995) present a wide diversity of trees that includes, in addition to alder (*Alnus firmifolia*, Fig. 6e), birch (*Betula pubescens*, Fig. 6e), pine trees (*Pinus teocote*), widespread strawberry trees or madroño (*Arbutus xalapensis*, Fig. 6b, c, f), oaks (*Quercus* spp.), and yuccas (*Yucca filifera*, Fig. 6b). Vegetation inside the crater is distinct from that on the outer-slopes and varies with the slope orientation. The north-facing, slopes are covered by a fir forest (*Abies religiosa*, locally named abeto or oyamel, Fig. 6b) whereas the south-facing slopes are dominated by grass and small shrubs (*Muhlembergia macroura*, *Arctostaphylos pungens,* and *Festuca tolucensis*). Vegetation on the lavas depends mostly on the tephra cover (Fig. 6c). Tephra-free lavas (late lavas) are not cultivated and have just a few pine trees (*Pinus hartwegii*). In contrast, lavas that are covered by tephra (early lavas) have a mature forest of *Pinus teocote* regenerated with *Pinus leiophylla* (Fig. 6g), in addition to strawberry trees (*Arbutus xalapensis*), succulents (*Sedum oxypetalum*), and grass. An area south of the cone that was not covered by Xitle lavas features cultivated fields (Fig. 6c). Associated and conspicuous native vegetation in the area include thistle (*Cirsium ehrenbergii*), tepozán (*Buddleja cordata*), boneset (*Ageratina glabrata*), and maguey (*Agave salmiana*, Fig. 6a). All these plants are important hosts for pollinators such as bats, nocturnal butterflies, hummingbirds, bees, wasps, and beetles. Furthermore, the different plant species live in symbiosis with different types of mycorrhizal fungi that are extremely important for biogeochemical cycles and to maintain healthy soils, fulfilling many ecological functions such as carbon sequestration, nutrient translocation, soil stabilization and infiltration facilitator (Table 1).

Other Sites with Similar Scientific Value

Other cones of the Sierra Chichinautzin present similar characteristics, although the cone and lava morphology, vegetation pattern, and soil cover vary widely with the volcano's age and location (altitude, precipitation) giving a chronosequence of volcanic deposits and soils (Peña-Ramírez et al. 2009). Cones that present particular interest for geosite development due to their easy access and good level of knowledge are Teuhtli (Siebe et al. 2005; Guilbaud et al. 2015), Pelado (Lorenzo-Merino et al. 2018), Dos Cerros (Agustín-Flores et al. 2011; López-Valdés 2019), and Chichinautzin (Siebe et al. 2004a, b; Peña-Ramírez et al. 2009; Reverchon et al. 2010).

Table 1 Associations between vegetation, soil type, altitude, and ecological functions for the Xitle volcano

Vegetation (species)	Mycorrhiza type	Altitude (masl)	Ecological functions	Soil type
Abedul forest (*Alnus* spp.)	Mainly ectomycorrhiza, with arbutoid, ericoid, and arbuscular associations	3000	Carbon sequestration, nutrient translocation, soil aggregate stability, better infiltration	Regosol
Fir patch (*Abies religiosa*)	Mainly ectomycorrhiza	3000	N availability and biogeochemical cycling	Regosol
Pinus forest (*Pinus teocote*) and pine scrub associated with strawberry trees (*Arbutus xalapensis*)	Ecto, arbuscular, and arbutoide mycorrhiza	2990–2800	Carbon sequestration, nutrient translocation, soil aggregate stability, better infiltration	Regosol in patches and Leptosol
Oak forest (*Quercus* spp.)	Ecto and arbuscular mycorrhiza	2700–2500	N and P cycling	Regosol and Leptosol
Xerophytic scrub (*Pittocaulon praecox*)	Mainly arbuscular	< 2500	P cycling, hydric stress, soil aggregate stability	Leptosol

Cuicuilco Geosite

Summary: This site encloses an archeological and ecological park that is located at the crossing of two main avenues in southwest Mexico City and several large shopping centers (Loreto-Pena Pobre or Cuicuilco, Periferico Sur), and hence represents a natural green island in a dense urban area with heavy traffic and a constant flow of people (Figs. 3d and 7a). The park has a round pyramid that was surrounded and partly covered by Xitle lavas (Fig. 7a), which superbly and very clearly illustrates the great impact of a relative minor eruption on a major urban area at the beginning of our era (González et al. 2000; Hubp et al. 2001). This place is also strategic for inferring the preexisting topography, climate, and human occupation, as well as the eruption chronology, through the study of the lava forms and the deposits preserved below (paleosols, embedded artifacts, ash) (Fig. 7b-d; Solleiro-Rebolledo et al. 2016). In addition, it includes a patch of the lava field with typical landforms and associated flora and fauna, which can be observed along pleasant walking paths (Fig. 7e). The top platform of the pyramid provides clear views over the southwest corner of the Mexico basin and the northern slopes of the Sierra Chichinautzin, featuring specifically the Xitle cone and Ajusco stratovolcano. On clear days (a rare occurrence), the Teuthli cone and the Popocateépetl stratovolcano can be seen to the southeast. Of cultural and artistic significance, the recently restored sculptures and monuments of the Ruta de la Amistad (friendship route) built directly on the lava can be observed on a nearby roundabout (Camarena-Berruecos 2010). Onsite, there is a small museum that presents basic information about the setting and archaeological findings. There is also a painting representing the destruction of the pyramid by the Xitle eruption.

Archaeological Interest The rounded pyramid is one of the few existing in Mexico and is, with the exception of small mounds nearby, the only remaining building of Cuicuilco City (Cummings 1926). Cuicuilco (700 BP–150 AD) is considered the first major urban center in the Mexico Basin (Heizer and Bennyhoff 1958), with a peak occupation of > 20,000 inhabitants (Sanders et al. 1979; Parsons 1989). Its great economic and political power is reflected by a majestic complex of buildings surrounding a temple with a conical truncated base, about 110 m in diameter and 20 m in height. There is still considerable

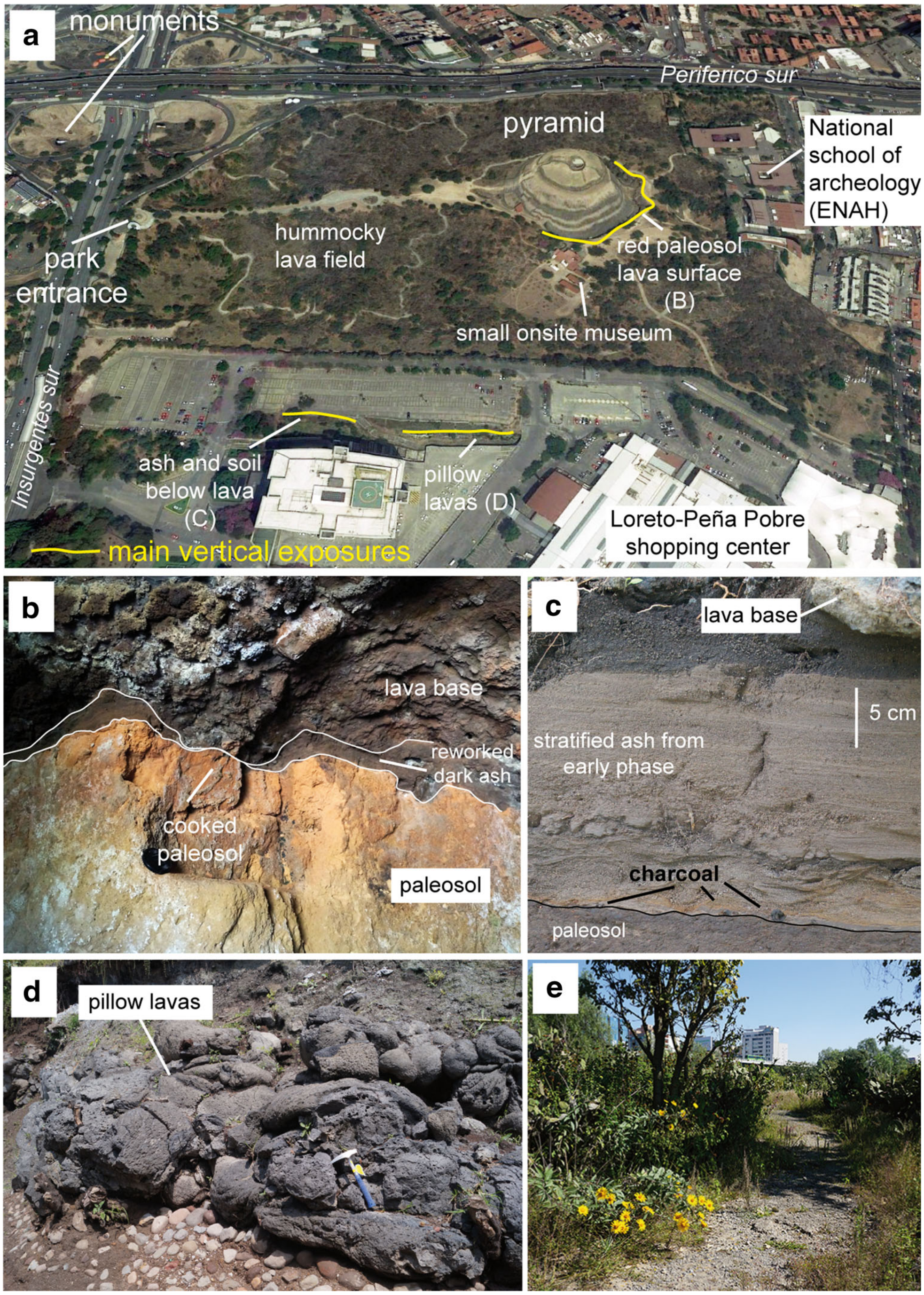


Fig. 7 Cuilcuilco geosite. a Cartography of main anthropic, archeologic, and volcanic elements on a slightly inclined view of satellite images draped over an elevation model from Google Earth. Capital letters indicate the location where the subsequent pictures were taken. b Photograph taken inside the tunnel excavated below the lavas, which shows the paleosol, ash layer, and lava base. c Photograph of a finely stratified, 17-cm-thick ash layer found just below the lava, at an outcrop located next to a building in the commercial center. Note the tiny dark charcoal bits found in the lowermost ash layer. Similar fragments were dated using radiocarbon by Siebe (2000) to obtain the age of the eruption. d Rounded pillow-type lavas exposed along the ground level of a car park in the commercial center. Archeologists obtained the permission in late 2018 to study this area in details because of the imminent occurrence of major building works. e Photograph taken at the start of one of the pedestrian paths that cross the lava field surrounding the pyramid. Note the pleasantness of the path provided by the vegetation and the slightly irregular ground. One of the tall buildings constructed along the Periferico Sur avenue is visible in the background, highlighting the close vicinity of one of the busiest roads in Mexico City

debate over whether the eruption directly caused the abandonment of Cuicuilco and the migration of its population to Teotihuacan or if both events are not connected. If it did, then the eruption caused a major natural disaster (e.g., Heizer and Bennyhoff 1958, 1972; Córdova et al. 1994; Siebe 2000; Urrutia-Fucugauchi et al. 2016).

Scientific Interests: Stratigraphy and Paleoenvironment The archaeological excavations created numerous cuts through the lava that reveal the vesicular interior of the flows and, more peculiarly, the surface below. A tunnel excavated below the lava exposes from top to bottom: the billowy base of the lava that is proof of its emplacement as inflating pahoehoe lobes, a thin reworked dark ash layer produced by early explosive activity at the cone, and a buried soil (paleosol) that is locally indurated and transformed into red brick due to the lava heat (Fig. 7b, Solleiro-Rebolledo et al. 2016). Such a succession very clearly shows the chronology of events that occurred at this important site, being hence of scientific and educational value. This paleosol preserves important information on the paleoclimate and human occupation at the time of the eruption (Solleiro-Rebolledo et al. 2016). The ash below the lava is locally finely stratified, indicative of an intense activity with rapidly succeeding strong explosions, and the basal layer contains bits of charcoal which were likely produced by the burning of vegetation along the advancing lava flow front (Fig. 7c, Siebe 2000). South of the archaeological park, a cut along a car park in a commercial center exposes rounded, pillow-like lava forms that suggest the existence of shallow water in that area at the time of the eruption (Fig. 7d; Plaza Cuicuilco in Palacio and Guilbaud 2015). This confirms other inferences that the pre-Hispanic city was located in a deltaic plain, at the convergence of river streams that flowed down the slopes of Ajusco (e.g., Córdova et al. 1994). Exposed recent pillow lavas are a rare feature, giving particularly high importance to this site.

Other Sites with Similar Scientific Value

The contact of the lava with the underlying ground, with a thin ash layer and locally burnt paleosol with archeological artifacts, can also be seen in several sites in UNAM, indicative of the large area occupied by settlements that were affected by early ash from Xitle (Entrada Principal and Campo de Beisbol in Palacio and Guilbaud 2015). Graves and diverse types of objects were found in the paleosol in the Copilco quarry located north of UNAM (Gamio 1920). However, this important site that was public from the 1920s to the early 1980s (Solleiro-Rebolledo et al. 2016), is now only accessible after specific request, from the offices of the National Institute of Anthropology of Mexico.

The Geopedregal Geosite

Summary: The ecological reserve of UNAM is the largest remaining area where the distal part of the Xitle lava flow field and its related ecosystem can be observed. Because of the need for conservation and the high potential threats, the core part of the reserve is closed to visits, but the campus encloses a total of 48 ha of *pedregales remanentes* that are remaining patches of the lava field not destroyed by infrastructure and not covered by a thick layer of construction material waste forming anthropogenic Technosols (SEREPSA 2008). The Geopedregal site was created in 2012 on a ca. 3000 m^2 lava outcrop located on land shared by the institutes of Geology and Geography. The site, originally used as dump, was cleaned, restored, and converted into a small park. This exposes in a preserved environment the main aspects of the lava morphology and related biological adaptations, ecosystem services such as thermal regulator, pollution buffering and pollinator corridor of bats, bumble bees and butterflies, as well as water capture by infiltration. It is also an aesthetically pleasing area (González et al. 2016). The site is used to conduct several research programs, field work, and science education for school and university students of different levels. It is also used for photographic expositions and guided visits, as well as local festivities that draw people from the nearby research centers to the site and help to secure its existence (see Electronic Supplementary Material and http://www.geologia.unam.mx/contenido/geopedregal). It is the first *pedregal remanente* of the University campus with a whole program of restoration, which is protected by the University laws (Zambrano et al. 2019).

Scientific Interests: Volcanology Lava structures in the Geopedregal site are varied and characteristics of a hummocky pahoehoe lava field like that observed in Kilauea volcano, Hawaii (Hon et al. 1994). This type of lava surface morphology has not been described elsewhere in Mexico, because of the rareness of basaltic magmas along the volcanic belt, hence being relevant for investigation and education. The main lava structures consist on an elongated, planar sheet lobe with steep lateral margins and an oval dome-shape tumulus with axial and lateral clefts, that are separated by a depression (lava rise pit) (Fig. 8a). There are also an area with complex ropey features caused by folding of the thin and still-plastic, hot lava crust during emplacement (Fig. 8b); an artificial cut that exposes the vesicular upper crust of the sheet lobe (Fig. 8c); an elongated cave that formed by partial lateral collapse of a tumulus (Fig. 8d); and two connected semi-circular 1.5-m-deep cavities that probably formed by roof collapse of a local tube (skylights, Fig. 8e). The lava's microtexture varies from smooth and slightly spiny to folded and show toothpaste-type texture in places. The variety in lava morphologies in this small area makes it particularly geodiverse and gives it high didactic value.

Pedology The age of the emplaced lava is less than 1700 years, and therefore, soils are very shallow (< 4 cm) and located only in small morphological depressions, allowing almost a continuous rock surface. They contain less than 20% of fine particles and low amounts of nutrients as cations (Ca, Mg, K, and Na) but high organic matter, classifying as nudilithic Leptosol hyperskeletic distric soils (Fig. 8f, Table 2, Siebe et al. 2016). From the point of view of soil quality, one could say that site quality is poor: soil texture is coarse, causing excessive drainage and low water holding capacity, nitrogen retention is limited because the organic horizon is thin, but the main function of these soils is infiltration and aquifer recharge. The diversity in lava morphology in terms of slope, roughness, and fracture pattern, and associated soil thickness, produces high biodiversity through the crucial role of microsites (or microhabitats) (Cano-Santana et al. 2006; Castellanos-Vargas et al. 2017).

The lavas around the Geopedregal have been covered with anthropic materials introduced in the early 1970s to build the green landscaped areas of the university covered with lawn,

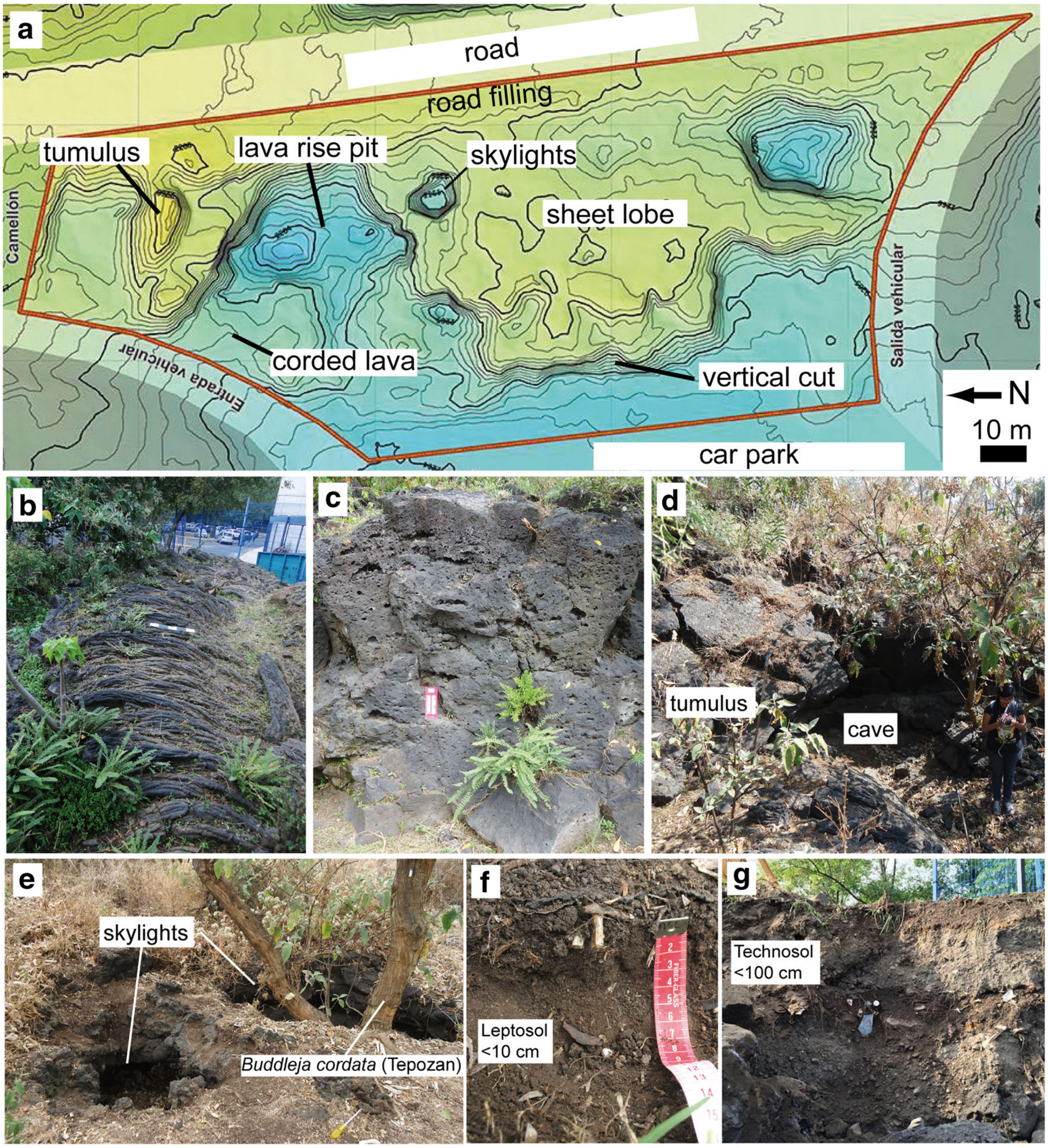


Fig. 8 Geopedregal geosite. a Topographic map showing the distinct volcanological elements described in the text. Adapted from figure made by P. Leautaud. b Photograph of the corded lava features. c Photograph of the vertical section across the lava that displays the typical upward increase in vesicle density and decrease in vesicle size that is observed in pahoehoe lavas and is symptomatic of a growth by inflation. Note also the vegetation growing in the small fractures (cooling joints) in the lava. d Photograph of the oval-shaped tumulus that borders the site and present a lateral cave that is occupied by bats and other local fauna. e Photograph of the jointed skylights that formed on the sheet lobe. Note the relatively large Tepozán tree that grew from inside the cavity. f Photograph of the typical type of soil that forms locally on the lava (see text and Table 2 for description). g Photograph of the anthropogenic Technosol soil observed on top of the lava, along the road. Note the occurrence of man-made objects within the soil (mostly made of plastic) and gravel

where technosols are developed that are now at least 1.5 m thick (Fig. 8g). These two contrasting types of soil (natural vs antropogenic) allow us to explain the ecosystem services provided by the natural lava soils.

Biodiversity Depending on the microhabitats with differential temperature, humidity and light conditions diverse plant species and community consortia can develop. These range from cryptobiotic saxicola crust (crust made by organism growing directly on the rock) made by an association of cyanobacteria, lichens, and bryophytes, to scrub vegetation dominated by the palo loco, agaves, and several terrestrial orchids. Some trees species (Tepozán: *Buddleja cordata*, Fig. 8e; Encino: *Quercus rugosa*;

Table 2 Properties of soils in the Xitle catena

A. Haplic Regosol, tephric, skeletic (humic)						Date: 02.02.2020					
Position: Top west hillside of Xitle Volcano						Parental material: Xitle cone tephra					
Vegetation: Oak-Pine forest with a high arbustive and perenial coverage						Described by V. Peña, H. Cotler, S. Cram					
Depth (cm)	Color (Munsell)	Texture	Structure	Stones	AD	pH	Roots	In situ humidity (pF)	Porosity	AS	Limit	Horizon
2–0	litter											Litter
0–2	10YR 2/2	AC	Granular	25	< 1	6	High	3 (moist)	Very high	High	Uniform	Ah1
02–17 cm	10YR 2/1	AC	Medium-weak subangular	30	1	6	Very high	3 (moist)	Very high	Low	Gradual	Ah2
17–36	10YR 2/1	AC	Medium-weak subangular	70	1	6	Very high	4 (dry)	Very high	Low	Gradual	1Cw
36–50	7.5YR2.5/1	AC		90	1,1	6	High	4 (dried)	Very high	Without	Abrupt	2Cw
> 50							Low					Tephra
B. Nudilithic Leptosol hyperskeletic (distric)					Date: 01.10.2017							
Position: Plateau lava in the REPSA, UNAM campus					Parental material: Xitle basaltic lava							
Vegetation: *Pittocaulon praecox* shrub					Described by M. P. Ortega-Larrocea							
Depth (cm)	Color (Munsell)	Texture	Structure	Stones	AD	pH	Roots	In situ humidity (pF)	Porosity	AS	Limit	Horizon
1–0	litter											Litter
0–1	10YR 2/2	AC	Granular	Low < 10%	< 1	5,4	Very high	3	Very high	High	Gradual	Ah1
2–4 cm	10YR 2/1	AC	Granular	Low < 10%	< 1	5,5	High	3	High	High	Gradual	Ah2
4–9 cm	10YR 2/1	AC	Medium-weak subangular	Low < 10%	< 1	6	High	3	High	High	Gradual	1Cw
> 9 cm											Basaltic lava	

Soil classification according to IUSS Working Group WRB (2015)

AC loamy sand texture, *AD* apparent density (g cm^{-1}), *AS* aggregate stability

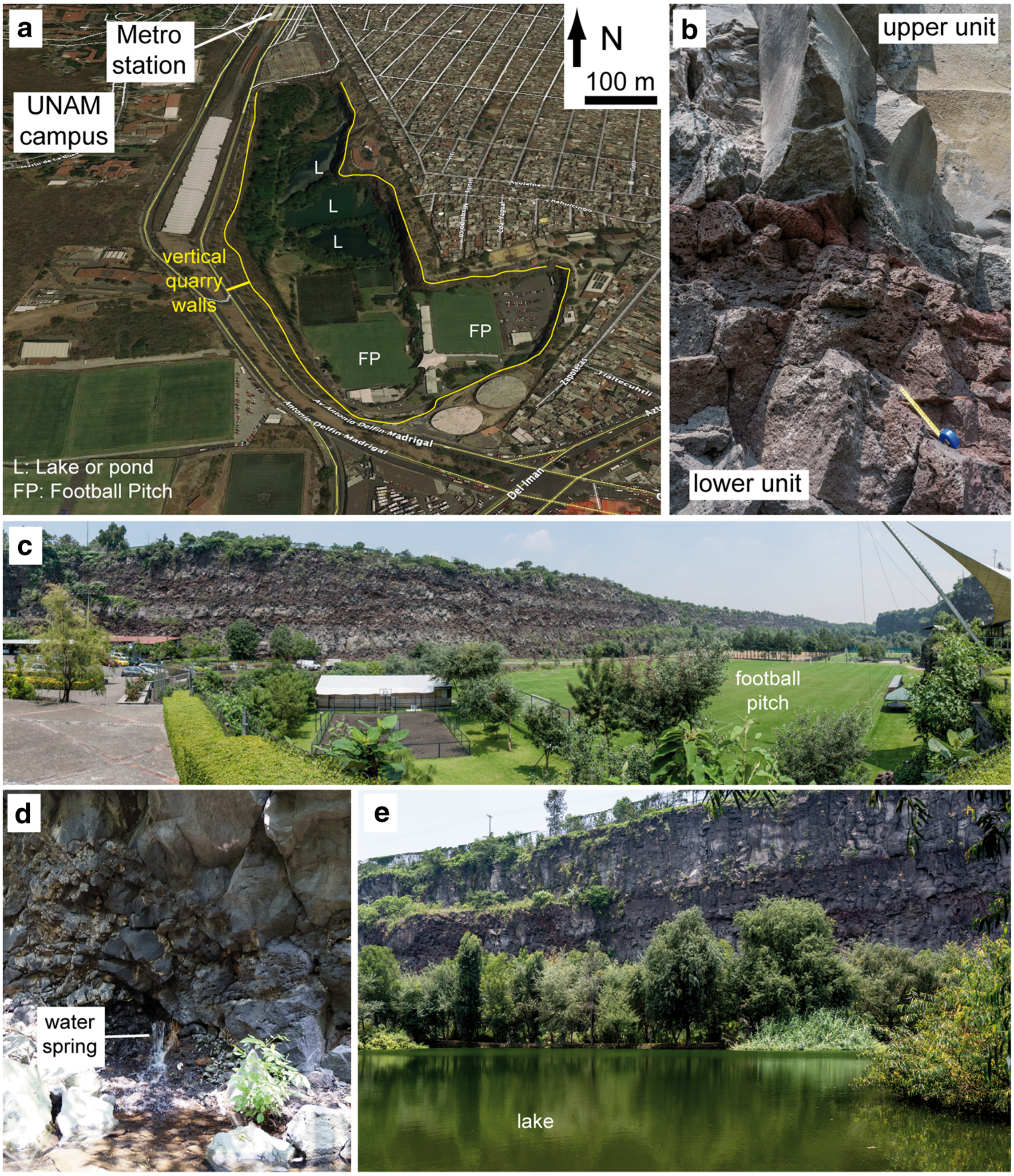


Fig. 9 Pumas quarry geosite. a Map of the Pumas quarry or Cantera Poniente. Note its location between the UNAM campus to the west, and the densely populated Santo Domingo popular borrow to the east. b Contact between two flow units exposed along the quarry walls. Note the reddish (oxidized) vesicular upper crust of the lower unit and denser, light-gray internal core of the upper unit. c Panoramic photograph of the site that shows the largest football pitch and the quarry walls, as well as the surrounding green areas. d Photograph of a water spring that can be seen along a walking path at the base of the highest quarry wall along the western border of the site. e Photograph of the lake and the eastern quarry wall in the background, taken from a walking path. Note the pleasant green setting and peculiar vegetation

Copal: *Bursera fagaroides* and *Bursera cuneata*) grow in skylights and deep inflation clefts. Orejas de burro (Crassulasean *Echeveria gibbiflora*) typically grows in fractures and shallow inflation clefts as well as cactus (nopal: *Opuntia tomentosa*, *Mammillaria magnimamma*, and the endemic *Mammillaria haageana san-angelensis*), and the bat-pollinated agave *Manfreda brachystachya* grows on flat surfaces exposed to abundant sunlight. The irregularity for the surface and the presence of caves also promotes significant diversity in fauna, such as local mammals and insects (marsupial Tlacuache *Didelphis virginiana*, ringtail Cacomixtle *Bassariscus astutus*, rodent Ratón piñonero *Peromyscus gratus gratus*, and the endangered bat *Leptonycteris curasoae*).

Other Sites with Similar Scientific Value

Some sites in the reserve buffer zone also allow visitors to observe the peculiar lava morphology and partly restored ecosystem (Jardín Botánico, Senda Ecológica and Espacio Escultórico, in Palacio and Guilbaud 2015). In some places in the UNAM campus and around, the lava surface is periodically cleared of invading grass (mostly for aesthetic purposes), conveniently exposing the lava's microstructures and textures. Outside of UNAM, the lava and vegetation are partly preserved in localized parches in the Cuicuilco site (Fig. 3d), the Bosque de Tlalpan (ID8 in Palacio and Guilbaud 2015), the Huayamilpas park in Santo Domingo, Los Encinos area near the Colegio de Mexico, the main avenues of the Jardines del Pedregal residential area, and the Anahuacalli museum (location of sites on Fig. 4; Cano-Santana et al. 2006; Camarena-Berruecos 2010).

The Pumas Quarry Geosite

Summary: The Cantera Oriente (eastern quarry in Spanish) is located at the eastern border of the UNAM campus (Fig. 9a). Despite its location near to one of the busiest metro stations of the capital (Universidad station), this place is very quiet green area that was restored with exotic plant species and contains a lake. This site is known informally as the Cantera de los Pumas because it encloses the training grounds of the infamous Pumas UNAM football team, and visits are allowed only by appointment. The 7.5-ha area belongs to UNAM but was exploited by the city from 1970 to 1994 (Lot 2007). The remaining artificial cuts of the quarry walls display spectacular exposures across an up to 40-m-thick pile of inflated pahoehoe flows (sheet lobes and tumuli). These are continuous over a lateral distance of 900 m and consists of five main vertical units (Fig. 9b, c; ID2 in Palacio and Guilbaud 2015). The high total thickness of the lava and its complex internal structure points to years of slowly advancing lobes, progressively filling a large depression (Guilbaud and Siebe 2009). Water springs emerge from fractured areas near the base of the lava pile (Fig. 9d) and feed a pond or small lake that covers 12,000 m^2 (Fig. 9e), demonstrating the role of the lava as an aquifer. This small lake is surrounded by a green area managed by the reserve that has some interest in biology and ecology (Lot 2007) as for example the conservation of the endemic Mexican salamander *Ambistoma mexicanum*.

Scientific Interests: Volcanology and Paleomagnetism The Cantera Oriente is the largest remaining quarry in the Xitle lava which has not been urbanized and where the lava can still be easily seen and accessed for sampling, which is of considerable interest for scientific studies. As introduced in the "Characterization of the Xitle Volcano Area: Geological, Environmental, and Additional Values" section, the Xitle lava is probably the most excavated young basaltic lava in the world, due to the growth of one of the largest cities in the world, first near its margins and then directly on it. In that respect, the Pumas quarry is the location where, to our knowledge, the thickest pile of young basaltic lava fed by a single eruption has been found in Mexico. Such continuous vertical exposure provides an excellent opportunity to study changes in the properties of basaltic lava at both small spatial and short temporal scales. Samples from this site have thus been used to assess the consistency of paleomagnetic measurements (Alva-Valdivia 2005) and a study of lava's chemical variations at that location is ongoing, with the aim to shed light on processes taking place during such monogenetic eruptions. This site is also important for interpreting the mode of growth of the lavas by the inflation process (or swelling) that creates the specific internal structure of the lava (vesiculated crust at the base and top, dense core) and the formation of the sheet lobes and tumuli that have planar and uplifted geometries, respectively. These features that are exceptionally well displayed by the quarry walls are typical of pahoehoe lavas observed in a wide range of settings and diagnostic of long-lived, far-reaching lava flows (Self et al. 1998). They are hence significant for the study and understanding of effusive basaltic eruptions worldwide.

Biology and Ecology Environmental and ecological aspects of the Pumas quarry are significantly distinct to other parts of the ecological reserve, motivating their management as a separate entity, and the publication of a dedicated field guide by Lot (2007). The specificity of the area and its main interest is the lacustrine environment that is now rare in the Mexico Basin but was common in the past, prior to drainage of the paleolakes. In that respect, this area may be considered as a snapshot of the pre-urban environment in the Mexico Basin. Rather unexpectedly given the high degree of transformation of the area and introduction of exotic species, the small lakes contain a rich aquatic fauna and flora, many of these native, endemic, of restricted distribution, and some even relict or rare elements with respect to their presence in the Mexico Basin (Lot 2007). The isolation of this area that is surrounded by an up to 40 m wall of lava and which access is restricted, makes it an ideal laboratory for research investigations, and gives it high landscape and aesthetic values.

Other Sites with Similar Scientific Value

There are many other places in UNAM where the typical internal structure of inflated pahoehoe is displayed, although at smaller scale than at the Pumas quarry. A site at the main entrance of the campus displays a long and continuous vertical cut in a sheet lobe (ID5 in Palacio and Guilbaud 2015). There are also deep cuts along the northwestern side of the Olympic Stadium, in the Casa Club del Académico, and along Insurgentes, the main avenue that crosses the University. These sites are extensively used for rock climbing, including by professionals for training, another interesting use of vertical lava outcrops.

Many other ancient quarries in the Xitle distal lavas were converted into housing complexes or commercial centers, where the internal structure of the lava is still exposed in places (for example: Copilco, La Cantera, Oasis). It is fairly common to find large outcrops inside schools, gardens, house basements, etc., across the entire flow-field, and several located along the most distal limit of tCde water springs from the lava base.

State of Conservation and Risk of Degradation of the Proposed Geosites

Exposures of the Xitle volcano and its lavas are threatened with serious damage to complete disappearance, due to the uncontrolled expansion and densification of Mexico City in the southwestern part of the Mexico basin (Cano-Santana et al. 2006; Hernández-Robles 2019). In most urbanized parts of the lava field, the original landform is hardly recognizable, and rock outcrops are scarcely found, being completely covered by concrete. Despite their significance, all the geosites described in this paper show signs of degradation and constant threats from building over. Despite being part of conservation land (suelo de conservación, GDF 2012), the vent area is invaded by illegal settlements that cover an increasing part of the area and damage irreversibly the volcanic products and associated biodiversity (Pezzoli 2000; Aguilar and Santos 2011). During the last decades, the Cuicuilco archeological site was severely fragmented and partly destroyed in order to build a large commercial center, as well as governmental and commercial offices. Only recently, a program was initiated to restore part of it, but the destruction is irreversible (Pérez-Galicia and Pérez-Campuzano 2015).

The UNAM campus that was the first large area of the lava that was urbanized is now, paradoxically, the largest preserved area. The ecological reserve that is the main actor in this conservation has continuously expanded since its formation, but the ecosystem is severely damaged, in a large part due to the introduction of exotic species, and it is subject to abundant and highly diverse threats directly related to the high traffic of people and cars within the university city (e.g., 70,000 cars per day; Zambrano et al. 2016). The annual budget and human resources of the reserve are clearly insufficient to restore and protect this area, and its very existence is not guaranteed as it relies on a decree that could easily be canceled by the rector of the university. The UNESCO World Heritage nomination guarantees the preservation of the architectonic heritage in the center of the campus; however, the lavas are not mentioned in the description of the property, and are hence of low relevance for UNESCO at this moment.

Quantitative Assessment

To evaluate quantitatively the significance of the proposed geosites and compare their scientific, educational and touristic values, we applied the assessment method of Brilha (2016) and show a summary of the results in Table 3. Specific methods have been developed for assessing the touristic values of urban geomorphosites (Clivaz and Reynard 2018; Pica et al. 2016, 2017); nevertheless, we argue that the more general method of Brilha (2016) allows a useful comparison of the Xitle geosites and effectively highlights the elements that impact negatively on their value and may be improved in the future. Besides, the Xitle geosites are all visible landforms whose value assessment does not require considering abundant archaeological and historical data, such as for deeply transformed, “invisible” geomorphosites in European cities (Nistor et al. 2017; Pica et al. 2017; Ticar et al. 2017; Clivaz and Reynard 2018).

Results show that in terms of scientific value, the vent area ranks first, closely followed by the Cuicuilco site, then the Pumas quarry, and last, the Geopedregal site. Such ranking mostly reflects the lack of international publications and lesser geodiversity for the latter two, while the vent area is more geodiverse for the variety in geoforms and volcanic products and has less use limitation (i.e., for sampling) than Cuicuilco. However, in terms of touristic and educational potential, the vent area ranks last for its higher vulnerability (because of illegal settlements and no fencing) and lack of dedicated parking area and safety facilities (stairs, etc). Cuicuilco ranks first in these categories for its ease of access by groups and its uniqueness.

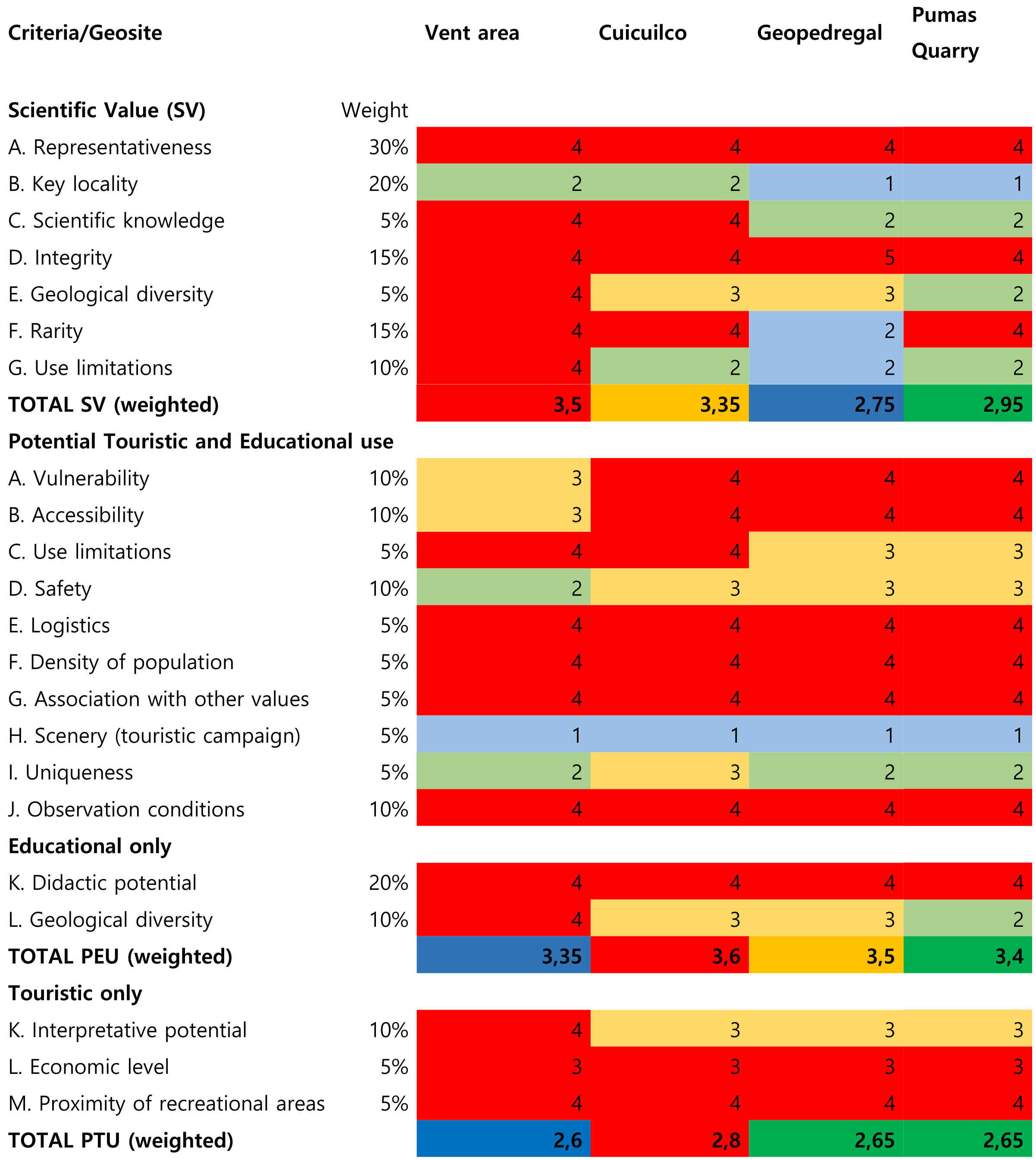
For the vent area, restricted access could be balanced by viewpoints and the score could be increased for facilities with a dedicated investment in infrastructure. The publication of ongoing research at the Pumas Quarry and Geopedregal sites will soon increase their scientific value.

It is noteworthy that some criteria had identical values for all 4 geosites. They all had the highest grade for representativeness, integrity, association with other values, observation conditions, and didactic potential, which is consistent with our purpose (they were selected precisely for these criteria). However, they all have low scenery value, given that the criterion used by this method is the promotion of the sites by touristic campaigns that are nonexistent for natural sites in Mexico City. Nonetheless, the city setting promotes their proximity to large accommodation facilities and recreational areas, a high population density, and high economic level (compared to national average). The way the geoheritage value of the geosites could be enhanced is discussed in the “Local Sustainable Development and Geoeducation Through Geoheritage: Ongoing Initiatives and Future Opportunities” section.

Benefits of the Xitle Geoheritage to the City

Based on our study of the Xitle geoheritage, we review more extensively its relevance for wider issues such as nature preservation and sustainability ("Relevance for Nature Preservation, Ecosystem Services, and Sustainability in the Context of Urban Development"), social equity ("Relevance for Providing Well-being and Reducing Social Inequalities"), and awareness on natural hazards ("Relevance for Mitigation and Education on Natural Hazards"). We finally expose an existing initiative led by academics at UNAM to promote this geoheritage and point to avenues for an amplification of these, to guarantee the preservation of the sites and foster their sustainable use by the city ("Local Sustainable Development and Geoeducation Through Geoheritage: Ongoing Initiatives and Future Opportunities").

Table 3 Geosite assessment following Brilha (2016)



Criteria/Geosite		Vent area	Cuicuilco	Geopedregal	Pumas Quarry
Scientific Value (SV)	Weight				
A. Representativeness	30%	4	4	4	4
B. Key locality	20%	2	2	1	1
C. Scientific knowledge	5%	4	4	2	2
D. Integrity	15%	4	4	5	4
E. Geological diversity	5%	4	3	3	2
F. Rarity	15%	4	4	2	4
G. Use limitations	10%	4	2	2	2
TOTAL SV (weighted)		**3,5**	**3,35**	**2,75**	**2,95**
Potential Touristic and Educational use					
A. Vulnerability	10%	3	4	4	4
B. Accessibility	10%	3	4	4	4
C. Use limitations	5%	4	4	3	3
D. Safety	10%	2	3	3	3
E. Logistics	5%	4	4	4	4
F. Density of population	5%	4	4	4	4
G. Association with other values	5%	4	4	4	4
H. Scenery (touristic campaign)	5%	1	1	1	1
I. Uniqueness	5%	2	3	2	2
J. Observation conditions	10%	4	4	4	4
Educational only					
K. Didactic potential	20%	4	4	4	4
L. Geological diversity	10%	4	3	3	2
TOTAL PEU (weighted)		**3,35**	**3,6**	**3,5**	**3,4**
Touristic only					
K. Interpretative potential	10%	4	3	3	3
L. Economic level	5%	3	3	3	3
M. Proximity of recreational areas	5%	4	4	4	4
TOTAL PTU (weighted)		**2,6**	**2,8**	**2,65**	**2,65**

Note that some criteria are used to calculate both the PEU and PTU. Cells with the highest values (4 and 5) are colored in red, medium-high value (3) in orange, medium-low (2) in green, and low (1) in blue

PEU potential educational use, *PTU* potential touristic use

Fig. 10 Photographs of two locations in the urbanized part of the Xitle lava flow-field, that highlight the higher state of preservation of outcrops and biological elements and related higher pleasantness of the environment, in a rich (Jardines del Pedregal) versus a poor (Santa Ursula) district. Pictures taken using the Street View option on Google Earth application

Relevance for Nature Preservation, Ecosystem Services, and Sustainability in the Context of Urban Development

Geosites are celebrations of nature and its link with humanity. In cities, nature tends to disappear under the pressure for construction and economic growth. Geosites are hence crucial for preserving remnants of natural elements in an otherwise sterile environment and should be considered as a key component for conservation (Gordon et al. 2018). Xitle geosites are particularly important in that respect, for the close relationship that exists between their geodiversity and the associated diversity in soils (pedodiversity) and flora and fauna (biodiversity). The Mexico Basin has suffered extremely rapid and destructive urban growth during the last 50 years, and the preservation of the last remains of fauna and flora that is endemic of this region and unique in the world strongly relies on the conservation of the Xitle lavas, whose elevated diversity in morphology and vesicularity creates a wide range of microhabitats that host a considerable number of species (e.g., Estañol-Tecuatl and Cano-Santana 2017).

Moreover, Reynard et al. (2017) argues that, in addition to being sites of interest for society that are located within the limits of the urban space (*lato sensu* definition), urban geosites can be places that help understanding the interaction between geological forces and urban development (*stricto sensu* definition). The Xitle geosites are a good example of urban geosites *stricto sensu*, as they remarkably conserve the testimony of the long-lasting interaction of volcanic activity with human development, during a ca. 2000-year period stretching from the eruption until today. Xitle lavas initially destroyed an early, large human settlement in the basin, creating a strong link between the geoheritage and the archaeological heritage of this region. Then, they slowed the expansion of the city because they were difficult to build on, hence controlling the pattern of urban development in the southwestern corner of the basin (note that main avenues surround the lava field's border, Fig. 4). Now they host the last natural areas and the country's main university, providing multiple ecosystem services to the city (habitat provision for endemic plants and animals, mitigation of flooding and damage by earthquakes, source of building and ornamental stones, water filtration and storage, recreation, outdoor sport, culture, identity, science knowledge, and education). The conservation of the open lava surface is particularly important for sustainability as its destruction through its coverage by cement, constructions or impermeable, exotic soils reduces drastically its capacity of infiltration, and hence preserving the original landforms is important for preserving water resources that may be fundamental in the future (Canteiro et al. 2019; Zambrano et al. 2019). In the UNAM campus alone, the cost of conserving open green areas with exotic tree species and lawn is very large in terms of water for irrigation, whereas the natural ecosystem sustains itself through the natural capacity of the lava to store water and the low requirements of water by endemic plants (Camarena-Berruecos 2010). In conclusion, the Xitle geoheritage should be explicitly included in natural conservation plans and urban planning strategies for the southwestern corner of the Mexico Basin, because of the multiple benefits it provides for the area.

Relevance for Providing Well-being and Reducing Social Inequalities

Nature preservation in cities strongly depends on urban planning and associated construction rules. These can vary spatially within cities, especially in countries with high inequalities such as Mexico. The preservation status of outcrops and associated biological elements in the urbanized part of the Xitle lava field varies widely, reflecting the economic and social segmentation of the city. Rich neighborhoods (e.g., Jardines del Pedregal) preserve outcrops and associated vegetation in nice parks, gardens, and, occasionally, caves in house basements, while in poor neighborhoods (e.g., Santa Ursula, Santo Domingo), every bit of lava is covered by concrete, vegetation is sparse and almost all non-native (Fig. 10), and the few remaining outcrops are used as dumps. The origin of such dichotomy is historical, as rich districts were designed by architects and engineers, whereas poor neighborhoods grew chaotically, from illegal settlements. These initial disparities were then amplified by the limited public funding to restore and maintain green areas. Hence, the remaining state of the lava outcrops in the city and quality of the environment (lamentably) reflects the distribution of economic wealth, amplifying social inequalities.

An important and highly valuable exception to this is the UNAM campus that preserves the largest ecological reserve of the area and numerous outcrops scattered across. Such areas are well maintained and accessible to all. The recently rehabilitated Huayamilpas park that is located in a popular district nearby is another public area that conserves a patch of the lava field. These natural green areas provide well-being for city dwellers, in particular those that have precarious housing, low-value jobs, and complex socio-economic conditions that do not allow them to travel to more natural, rural areas. Because they include walking and cycling paths, as well as climbing walls, the parks promote physical activity, of particular relevance in Mexico where child and adult obesity is among the highest worldwide. In addition to such services, we argue below that lava patches within the city should be used to disseminate information and raise awareness about natural hazards.

Relevance for Mitigation and Education on Natural Hazards

Nature under pressure increases dramatically the impact scale of natural hazards. At the time of writing, the COVID-9 pandemic is putting under lockdown at hundreds of millions of people worldwide, with tragic social, economic, and political impacts. Although this event has complex, multi-factual sources that will require years of investigation to untangle, it may be considered as an example of a small natural hazard (a virus hosted in an animal) that turned into a global disaster, partly due to the increasing interference of humans on wildlife and the environment (e.g., Bonilla-Aldana et al. 2020). Geosites are ways we can, as a community, restore links between society and nature, and acknowledge its relevance for our past, present and future. It also allows to promote a better communication and thrust between the population and the scientific community, which would allow, in the long term, to better mitigate hazards.

Geological hazards are an important and increasing threat to society simply because of population growth and the increasing densification of urban areas in hazardous locations. Such risk needs to be better recognized, to avoid both large-scale disasters in the future, and mitigate smaller, chronic ones that have a high social cost. Mexico City is an area where volcanic hazards are high, but most people lack formal education in geology and poorly understand the processes involved, creating the need for geoeducation. The Xitle area is a location where the impact of geological activity on society is well exposed, and can be hence easily divulgated. The Xitle eruption was a minor volcanic event in terms of magnitude, yet its impacts were great. The pyramid surrounded by lavas (Cuicuilco archeological site) is a clear physical evidence for past effects. At present, the impact of the lavas is mostly positive as they help mitigate chronic hazards such as inundations that occur every rainy season in the basin, and earthquakes that occur on a monthly to yearly base. The Mexico basin is a very dynamic system, both geologically and humanly, stressing the need for more holistic studies on human and hazard interaction, to minimize the risks. We argue that the preservation and investigation of the Xitle geoheritage is fundamental to better understand, mitigate, and inform on natural hazards in Mexico City.

Local Sustainable Development and Geoeducation Through Geoheritage: Ongoing Initiatives and Future Opportunities

Our study provides some insights about how the urban geoheritage could be promoted and enhanced. The quantitative assessment of the geosites shed some light into how the value of these and other sites could be improved, in order to envisage the creation of a geotouristic attraction such as an urban geopark.

The low scenery value of the sites is a feature that is common to all urban geosites as they are of small size and immersed into a dense urban framework with tall buildings (Pica et al. 2017). Therefore, they are poorly known by locals and even less by city tourists, and strategies are required to enhance their visibility. Their advantage, however, in comparison to most rural sites, is that they tend to be associated to significant additional cultural values, such as archaeology and history for Rome (Pica et al. 2017). Geosites at Xitle have great environmental (Xitle vent area), archaeological (Cuicuilco), ecological (Geopedregal), and recreational (Pumas quarry) values that are better known by the general public than their geological attributes. Such linkage should be used to draw people to the sites, to infuse them with geological knowledge.

Another clue to promote urban heritage is to involve local university and educational centers that are located near the geoheritage elements. As highlighted above, the UNAM campus is a key area for the preservation of Xitle geoheritage. The university is also the main research and education hub in the country. It should hence have a leading role in promoting such heritage. The two UNESCO Geoparks in Mexico (Comarca Minera and Mixteca Alta) that were nominated in 2007 were initiated by UNAM-based research groups and arose from the joint participation with municipal authorities, ejidatarios (managers of communal lands), and the local population. The geoparks continue to receive UNAM support through research projects, but they are managed by locals who are also the main beneficiaries.

The Geopedregal in the UNAM campus is the only geosite in the area with a planned series of educational activities related to the natural features present there, hence being an example to follow. Initially focused on the biological and ecological aspects, activities were gradually expanded to include geological aspects, in the context of the UNESCO Geoheritage for Geohazard Resilience project (ICGP 692). In 2019, the site obtained a certification to be incorporated in a national-wide program of school visits, which strongly promotes its educational use. The area itself is small, which limits the size of groups and number of features to be observed, but ideas for future development involve using it as a starting point for "geowalks" around the UNAM campus that would include other interesting sites. Cultural activities at the Geopedregal involve organizing social events that are highly important in Mexico, for example the Dia de Muertos, the 1st of November, for which people make highly elaborate and creative altars for the missing, or the posadas that occur 9 days before Christmas and consist in gatherings during which a meal is shared and a piñata is destroyed (Electronic Supplementary Material). Those initiatives allowed the site to be known by many, increasing its visibility and promoting its conservation in the future. This is an example of how the conduction of cultural activities can help raise awareness on local geology and ecology. The preservation of this site in the long term would although require hiring permanent, specifically dedicated personnel as much of the needed maintenance work and teaching is currently done by students. Didactic material incorporating geological information should also be developed and published formally.

The experience gained at the Geopedregal should be used to develop other sites in the UNAM campus (for example, a similar incipient project at the science faculty, or the Senda Ecologica near to the science museum Universum). The methods developed at UNAM should then be applied to the other geosites highlighted in this study, in close collaboration with the community and local actors, such as archaeologists at the Cuicuilco site, local guides at the parque ejidal San Nicolas Totolapan (a recreational park located near the vent area), and coordinators of the UNAM reserve and soccer training grounds at the Pumas quarry. People and organizations in charge of other interesting sites such as the Huayamilpas park, the Anahuacalli museum, and the Jardines del Pedregal could also be contacted, to promote the realization of geo-related outreach activities, such as the installation of information panels or the organization of activities and school visits. In the long term, all these initiatives could be merged to develop a geopark in the Xitle area.

With respect to international recognition and protection, the UNAM campus already hosts a UNESCO World Heritage site, but the nomination is purely cultural. Several aspects of the property are however strongly tied to the geology, as the acclaimed architecture include Xitle stone and was inspired by the original land aspect. The location of the UNAM campus itself is closely related to the lavas as they were the last un-urbanized spot at relatively close distance from the city center. There is hence potential to build a proposal to include the geological aspect in the nomination and make it a mixed site (natural + cultural). This study provides the foundation of such an initiative that should engage a wide range of academics and students from different faculties and research institutes in the themes of science, architecture and arts, as well as UNAM authorities, the local government (Delegación de Coyoacán) and the government of Mexico City.

Conclusions

Geoheritage in cities is commonly destroyed and undervalued, despite its significance for a wide range of issues that include nature preservation, education on natural hazards, and environmental sustainability.

Mexico City is a large, densely populated area with serious environmental and social problems that is also exposed to a multitude of natural hazards. The Xitle volcano provides one way, through geoheritage, of dealing with some of the city's problems. The Xitle eruption produced a small cone and an extensive lava field that have been incorporated into the city during the last 50 years of uncontrolled development.

We have chosen four exceptional geosites that expose major elements of geodiversity, biodiversity, and pedodiversity, and which link with anthropic activity, and hence are key locations for educating on sustainability and natural hazards. The geosites also provide ways to preserve the remaining natural spots in the city. They can be used to bring people to understand the relationship between volcanic and human activity, conserve and value key elements of the city's identity, improve human well-being, help lower social inequalities, and raise awareness on risks.

Urban geoheritage commonly lacks visibility, which could be improved by valuing the cultural values associated to the sites, and engaging local actors such as educational centers. Existing educational projects such as the Geopedregal at the national university should be consolidated and used as a basis to develop community-based projects at other sites. Initiatives such as creating an urban geopark or converting the UNESCO World Heritage cultural site of the university campus to a mixed cultural-natural site should be considered as ways to ensure the conservation of the Geoheritage and its multiple benefits to the city.

In general, this work shows how geoheritage developed on important geosites can incorporate all environmental, cultural, and social aspects, and how they could be used to maintain an awareness of the environment and natural hazards in an urban context.

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Authors' contributions MNG wrote the manuscript and made the figures. PO described biological elements and SC pedological elements at specific sites. BW revised the English and made valuable suggestions for the discussion. The four authors discussed the scientific, educational, and touristic values of the sites and the relevance of Xitle volcano for addressing multiple issues of the city.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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References

Aguilar AG, Santos C (2011) Informal settlements' needs and environmental conservation in Mexico City: An unsolved challenge for land-use policy. Land Use Policy 28(4):49–662. https://doi.org/10.1016/j.landusepol.2010.11.002

Agustín-Flores J, Siebe C, Guilbaud MN (2011) Geology and geochemistry of Pelagatos, Cerro del Agua, and Dos Cerros monogenetic volcanoes in the Sierra Chichinautzin Volcanic Field, south of México City. J Volcanol Geotherm Res 201:143–162. https://doi.org/10.1016/j.jvolgeores.2010.08.010

Alva-Valdivia LM (2005) Comprehensive paleomagnetic study of a succession of Holocene olivine-basalt flow: Xitle Volcano (Mexico) revisited. Earth Planets Space 57(9):839–853

Aragón-Durand F (2007) Urbanisation and flood vulnerability in the peri-urban interface of Mexico City. Disasters 31(4):477–494. https://doi.org/10.1111/j.1467-7717.2007.01020.x

Arce JL, Layer PW, Lassiter JC, Benowitz JA, Macías JL, Ramírez-Espinosa J (2013) 40Ar/39Ar dating, geochemistry, and isotopic analyses of the quaternary Chichinautzin volcanic field, south of Mexico City: implications for timing, eruption rate, and distribution of volcanism. Bull Volcanol 75:774

Arce JL, Muñoz-Salinas E, Castillo M, Salinas I (2015) The ~2000 yr BP Jumento volcano, one of the youngest edifices of the Chichinautzin Volcanic Field, Central Mexico. J Volcanol Geotherm Res 308:30–38

Arnold JR, Libby WF (1951) Radiocarbon dates. Science 113(2927): 111–120

Badilla-Cruz RR (1977) Estudio petrológico de la lava de la parte noreste del Pedregal de San Ángel, D.F. Bol Soc Geol Mex 38:40–57

Bloomfield K (1975) A late-Quaternary monogenetic volcano field in central Mexico. Geol Rundsch 64:476–497

Bonilla-Aldana DK, Dhama K, Rodriguez-Morales AJ (2020) Revisiting the one health approach in the context of COVID-19: a look into the ecology of this emerging disease. Adv Anim Vet Sci 8(3):234–237

Boothroyd A, McHenry M (2019) Old processes, new movements: the inclusion of geodiversity in biological and ecological discourse. Diversity 11(11):216. https://doi.org/10.3390/d11110216

Brilha J (2016) Inventory and quantitative assessment of geosites and geodiversity sites: a review. Geoheritage 8(2):119–134. https://doi.org/10.1007/s12371-014-0139-3

Brilha J, Gray M, Pereira DI, Pereira P (2018) Geodiversity: an integrative review as a contribution to the sustainable management of the whole of nature. Environ Sci Pol 86:19–28

Camarena-Berruecos P (2010) Xerojardinería. Guía para el diseño de los jardines de Ciudad Universitaria. Universidad Nacional Autónoma de México, Mexico City, p 92pp

Campillo M, Gariel JC, Aki K, Sánchez-Sesma FJ (1989) Destructive strong ground motion in Mexico City: Source, path, and site effects during great 1985 Michoacán earthquake. Bull Seismol Soc Am 79(6):1718–1735

Cañon-Tapia E, Walker GPL, Herrero-Bervera E (1995) Magnetic fabric and flow direction in basaltic Pahoehoe lava of Xitle Volcano. Mexico: J Volcanol Geotherm Res 65:249–263

Cañon-Tapia E, Walker GPL, Herrero-Bervera E (1996) The internal structure of lava flows-insights from AMS measurements I: Near-vent aa. J Volcanol Geotherm Res 70:21–36

Cano-Santana Z, Pisanty I, Segura S, Mendoza-Hernández PE, León-Rico R, Soberón J et al (2006) Ecología, conservación, restauración y manejo de las áreas naturales y protegidas del Pedregal del Xitle. In: Oyama K, Castillo A (eds) Manejo, conservación y Restauración de Recursos naturales en México. UNAM-Siglo XXI, Mexico City, pp 203–226

Canteiro M, Olea S, Escolero O, Zambrano L (2019) Relationships between urban aquifers and preserved areas South of Mexico City. Groundw Sustain Dev 8:373–380

Carrillo-Trueba C (1995) El Pedregal de San Ángel. Universidad National Autonoma de Mexico, Mexico City

Castellanos-Vargas I, García-Calderón NE, Cano Santana Z (2017) Procesos físicos del suelo en la reserva ecológica del Pedregal de San Ángel de Ciudad Universitaria: atributos para su conservación. Terra Latinoamericana 35(1):51–64

Clivaz M, Reynard E (2018) How to integrate invisible geomorphosites in an inventory: a case study in the Rhone River valley (Switzerland). Geoheritage 10(4):527–541

Córdova C, Martin del Pozzo AL, Camacho JL (1994) Palaeolandforms and volcanic impact on the environment of prehistoric Cuicuilco, Southern Mexico City. J Archaeol Sci 21(5):585–596

Cummings B (1926) Cuicuilco and the Archaic culture of Mexico. Sci Mon 23:289–304

Del Monte M, Fredi P, Pica A, Vergari F (2013) Geosites within Rome City center (Italy): a mixture of cultural and geomorphological heritage. Geogr Fis Din Quat 36(2):241–257

Del Moral R, Grishin SY (1999) Volcanic disturbances and ecosystem recovery. In: Walker LR (ed) Ecosystems of disturbed Ground. Elsevier, Amsterdam, pp 137–160

Delgado H, Molinero R, Cervantes P, Nieto-Obregón J, Lozano-Santa Cruz R, Macías-González HL, Mendoza-Rosales C, Silva-Romo G (1998) Geology of Xitle volcano in southern Mexico-City, A 2000 year-old monogenetic volcano in an urban area. Revista Mexicana de Ciencias Geológicas 15(2):115–131

Eakin H, Lerner AM, Manuel-Navarrete D, Aguilar BH, Martínez-Canedo A, Tellman B, Bojórquez-Tapia L (2016) Adapting to risk and perpetuating poverty: household's strategies for managing flood risk and water scarcity in Mexico City. Environ Sci Pol 66:324–333

Eiser JR, Bostron A, Bruton I, Johnston DM, McClure J, Paton D, van de Pligt J, White MP (2012) Risk interpretation and action: a conceptual framework for responses to natural hazards. Intern J Disaster Risk Reduction 1:5–16

Estañol-Tecuatl F, Cano-Santana Z (2017) Recovery of basalt substrate for xeric scrub restoration in a lava field in Mexico City. Ecol Restor 35(1):41–51

Fassoulas C, Watanabe M, Pavlova I, et al (2018) UNESCO Global Geoparks: living laboratories to mitigate natural induced disasters and strengthen communities' resilience. In: Natural hazards and disaster risk reduction policies. Il Sileno Edizioni, pp 175–197

Flores-Estrella H, Yussim S, Lomnitz C (2007) Seismic response of the Mexico City Basin: A review of twenty years of research. Nat Hazards 40(2):357–372. https://doi.org/10.1007/s11069-006-0034-6

Gamio M (1920) Las excavaciones del Pedregal de San Angel y la cultura arcaica del Valle de México. Am Anthropol 22(2):127–143

GDF (Gobierno del Distrito Federal) (2012) Atlas geográfico del suelo de conservación del Distrito Federal. Secretaría del Medio Ambiente, Procuraduría Ambiental y del Ordenamiento Territorial del Distrito Federal, México

González S, Pastrana A, Siebe C, Duller G (2000) Timing of the prehistoric eruption of Xitle volcano and the abandonment of Cuicuilco pyramid, southern Valley of Mexico. In: McGuire B, Griffiths D, Stewarts I (eds) The archaeology of geological catastrophes. Geol Soc London, Spec Publ 171, pp 205–224

González R, Estrada M, Orellana A, Bueno I, Segura S (2016) Saving islands within a city. Available online at: https://it.cornell.edu/ (accessed March 17, 2019)

Gordon JE, Crofts R, Díaz-Martínez E (2018) Geoheritage conservation and environmental policies: retrospect and Prospect. In: Reynard E, Brilha J (eds) Geoheritage. Elsevier, Chennai, pp 213–236

Górska-Zabielska M, Zabielski R (2017) Potential values of urban geotourism development in a small Polish town (Pruszków, Central Mazovia, Poland). Quaestiones Geographicae 36(3):75–86

Gray M (2013) Geodiversity: valuing and conserving abiotic nature, 2nd edn. Wiley, Blackwell ISBN: 978-0-470-74215-0

Gray M (2018) Geodiversity: the backbone of geoheritage and geoconservation. In: Brilha J, Reynard E (eds) Geoheritage Assessment, Protection and Management. Elsevier, Amsterdam, pp 13–25. https://doi.org/10.1016/B978-0-12-809531-7.00001-0

Guilbaud MN, Siebe C (2009) The lava flow-field of the ca. 1670 yrs BP Xitle eruption, México: structure and implications for eruption dynamics (abstract). In: Siebe C, Guilbaud M-N, Salinas S (eds) 250 Aniversario del nacimiento del volcán Jorullo en México: Morelia, Michoacán, Mexico. Impretei, Mexico City, pp 28–29

Guilbaud MN, Arana-Salinas L, Siebe C, Barba-Pingarrón LA, Ortiz A (2015) Volcanic stratigraphy of a high-altitude Mammuthus columbi (Tlacotenco, Sierra Chichinautzin), Central México. Bull Volcanol 77:17. https://doi.org/10.1007/s00445-015-0903-5

Hardoy J, Mitlin D, Satterthwaite D (2013) Environmental problems in an urbanizing world: finding solutions in cities in Africa, Asia and Latin America. Earthscan Publications Ltd, London

Heizer R, Bennyhoff JA (1958) Archaeological investigations of Cuicuilco, Valley of Mexico, 1956. Science 127:232–233

Heizer R, Bennyhoff JA (1972) Archaeological excavations at Cuicuilco, Mexico, 1957. Nat Geog Rep 1955-1960:93–104

Hernández-Robles HE (2019) Dinámica de cambio de uso de suelo y coberturas vegetales en el derrame de lava del volcán Xitle, Ciudad de México, 1993-2015. Undergraduate thesis, Facultad de Ciencias, UNAM

Hon K, Kauahikaua J, Denlinger R, Mackay K (1994) Emplacement and inflation of pahoehoe sheet flows, Observations and measurements of active lava flows on Kilauea Volcano, Hawaii. Geol Soc Am Bull 106:351–370

Hough M (2004) Cities and natural process. Routledge, London

Hubp J, Inbar M, Pastrana A, Flores A, Zamorano J (2001) Interpretation of the geomorphic setting of the Cuicuilco basin, Mexico City, affected by the pre-Hispanic eruption of the Xitle volcano/ Interprétation de l'environnement géomorphologique du bassin de Cuicuilco, ville de Mexico, affecté par l'éruption pré-hispanique du volcan Xitle. Géomorphologie: relief, processus, environnement 7(3):223–232

INEGI (2010) Censo de Población y Vivienda 2010. https://www.inegi.org.mx/programas/ccpv/2010/. Accessed 17 December 2020

Jim CY (2004) Green-space preservation and allocation for sustainable greening of compact cities. Cities 21(4):311–320

Jim CY (2013) Sustainable urban greening strategies for compact cities in developing and developed economies. Urban Ecosyst 16(4):741–761

Keszthelyi L (1995) A preliminary thermal budget for lava tubes on the Earth and planets. J Geophys Res Solid Earth 100(B10):20411–20420

Krieger P (2008) Lecciones inesperadas de Ciudad Universitaria y su reserva ecológica. Bitácora Universitaria 18:46–49

López-Valdés N (2019) Secuencia de eventos eruptivos recientes en el sector oriental de la Sierra Chichinautzin, Centro de México: Distribución, edad y composición química de lavas y tefras. Master thesis, UNAM, Mexico

Lorenzo-Merino L, Guilbaud MN, Roberge J (2018) The violent-Strombolian eruption of 10 ka Pelado shield volcano, Sierra Chichinautzin, Central Mexico. Bull Volcanol 80:27. https://doi.org/10.1007/s00445-018-1208-2

Lot A (2007) Guía ilustrada de la Cantera Oriente. Caracterización ambiental e inventario biológico. Coordinacion de la Investigacion Cientifica, Universidad Nacional Autonoma de Mexico, Mexico City

Lot A, Cano-Santana Z (2009) Biodiversidad del ecosistema del Pedregal de San Ángel. Universidad Nacional Autónoma de México, Mexico City

Luhr JF, Simkin T (1993) Paricutín, the volcano born in a cornfield, Geoscience Press, Phoenix, Arizona, pp 1–427

Mancebo F (2007) Natural hazards and urban policies in Mexico City. J Alpine Res. Revue de géographie alpine 95-2:108–118

Márquez A, Verma SP, Anguita F, Oyarzun R, Brandle JL (1999) Tectonics and volcanism of Sierra Chichinautzin: extension at the front of the Central Trans-Mexican Volcanic belt. J Volcanol Geotherm Res 93(1-2):125–150

Martin del Pozzo AL (1982) Monogenetic vulcanism in Sierra Chichinautzin, Mexico. Bull Volcanol 45:9–24

McKeever PJ, Zouros N (2005) Geoparks: celebrating Earth heritage, sustaining local communities. Epis 28(4):274

Nistor C, Mihai B, Toma L, Carlan I (2017) Photogrammetric modelling for urban medieval site mapping. A case study from Curtea de Argeş. Romania Quaestiones Geographicae 36(3):87–96

Ortiz-Zamora D, Ortega-Guerrero A (2010) Evolution of long-term land subsidence near Mexico City: Review, field investigations, and predictive simulations. W Resour Res 46(1):W01513. https://doi.org/10.1029/2008WR007398

Palacio JL, Guilbaud MN (2015) Patrimonio natural de la Reserva Ecológica del Pedregal de San Ángel y áreas cercanas: sitios de interés geológico y geomorfológico al sur de la Cuenca de México. Bol Soc Geol Mex 67(2):227–244

Parsons JR (1989) Arqueología regional en la Cuenca de México: una estrategia para la investigación futura. Anales de Antropología 26:1

Pavlova I (2019) Disaster risk reduction at UNESCO Global Geoparks and Biosphere Reserves. J World Herit Stud, Special issue 2019:73–77. https://doi.org/10.15068/00157689

Peña-Ramírez VM, Vázquez-Selem L, Siebe C (2009) Soil organic carbon stocks and forest productivity in volcanic ash soils of different age (1835–30,500 years BP) in Mexico. Geoderma 149(3-4):224–234

Pérez-Galicia A, Pérez-Campuzano E (2015) La complejidad del manejo de zonas de turismo (eco) arqueológico en ciudades. El caso de Cuicuilco, México. Pasos Revista de turismo y patrimonio cultural 13(5):1079–1094. https://doi.org/10.25145/j.pasos.2015.13.074

Pérez-Méndez A (2007) Las casas del Pedregal. Editorial Gustavo Gili, Mexico City 323p

Peterson FL (1972) Water development on tropic Volcanic Islands—Type example: Hawaii a. Groundw 10(5):18–23

Petrosino P, Iavarone R, Alberico I (2019) Enhancing social resilience through fruition of geological heritage in the Vesuvio National Park. Geoheritage 11:2005–2024. https://doi.org/10.1007/s12371-019-00404-y

Pezzoli K (1998) Human settlements and planning for ecological sustainability: the case of Mexico City. The MIT Press, Cambridge

Pica A, Vergari F, Fredi P, Del Monte M (2016) The aeterna urbs geomorphological heritage (Rome, Italy). Geoheritage 8(1):31–42

Pica A, Luberti GM, Vergari F, Fredi P, Del Monte M (2017) Contribution for an urban geomorphoheritage assessment method: proposal from three geomorphosites in Rome (Italy). Quaestiones Geographicae 36(3):21–36

Porta J, Poch RM, López-Acevedo M (2019) Edafología: uso y protección de suelos. 4ª Edición. Ediciones Mundi-Prensa, Madrid 624p

Portal C, Kerguillec R (2018) The shape of a city: Geomorphological landscapes, abiotic urban environment, and geoheritage in the western world: the example of parks and gardens. Geoheritage 10(1):67–78

Reverchon F, Ortega-Larrocea MDP, Pérez-Moreno J, Peña-Ramírez VM, Siebe C (2010) Changes in community structure of ectomycorrhizal fungi associated with *Pinus montezumae* across a volcanic soil chronosequence at Sierra Chichinautzin, Mexico. Can J For Res 40(6):1165–1174

Reynard E, Pica A, Coratza P (2017) Urban geomorphological heritage. An overview. Quaestiones Geographicae 36(3):7–20. https://doi.org/10.1515/quageo-2017-0022

Rivera D (1952) Requisitos para la organización del pedregal. Universidades de Latinoamérica 3(16):67-69. http://132.247.171.154:8080/handle/Rep-UDUAL/407. Accessed 17 Dec 2020

Rodrigues ML, Machado CR, Freire E (2011) Geotourism routes in urban areas: a preliminary approach to the Lisbon geoheritage survey. GeoJ Tour Geosites 8(2):281–294

Rzedowski J (1954) Vegetación del Pedregal de San Ángel (Distrito Federal, México). Anales Escuela Nacional Ciencias Biológicas, Instituto Politécnico Nacional 8:59–129

Salas Portugal A (2006) Morada de lava. Universidad Nacional Autónoma de Mexico, Mexico City 204p

Sanders WT, Parsons JR, Santley RS (1979) The Basin of Mexico: Ecological Processes in the Evolution of a Civilization. Academic Press, New York 561p

Schmitter E (1953) Investigación petrológica en las lavas del pedregal de San Angel. Congreso Científico Mexicano, Memorias 3:218–237

Schteingart M (1989) The environmental problems associated with urban development in Mexico City. Environ Urban 1(1):40–50

Self S, Keszthelyi L, Thordarson T (1998) The importance of pāhoehoe. Annu Rev Earth Planet Sci 26(1):81–110

SEREPSA (Secretaría Ejecutiva de la Reserva Ecológica El Pedregal de San Ángel) (2008) Manual de Procedimientos. Programa de Adopción de la Reserva Ecológica del Pedregal de San Ángel. Secretaría Ejecutiva REPSA, Coordinación de la Investigación Científica, Universidad Nacional Autónoma de Mexico, Mexico City 108 p

Siebe C (2000) Age and archaeological implications of Xitle volcano, southwestern Basin of Mexico-City. J Volcanol Geotherm Res 104(1-4):45–64. https://doi.org/10.1016/S0377-0273(00)00199-2

Siebe C, Macías JL (2006) Volcanic hazards in the Mexico City metropolitan area from eruptions at Popocatépetl, Nevado de Toluca, and Jocotitlán stratovolcanoes and monogenetic scoria cones in the Sierra Chichinautzin Volcanic Field. Special Papers-Geol Soc Am 402:253

Siebe C, Rodríguez-Lara V, Schaaf P, Abrams M (2004a) Radiocarbon ages of Holocene Pelado, Guespalapa, and Chichinautzin scoria cones, south of Mexico City: implications for archaeology and future hazards. Bull Volcanol 66(3):203–225

Siebe C, Rodríguez-Lara V, Schaaf P, Abrams M (2004b) Radiocarbon ages of Holocene Pelado, Guespalapa, and Chichinautzin scoria cones, south of Mexico City: implications for archeology and future hazards. Bull Volcanol 66:203–225. https://doi.org/10.1007/s00445-003-0304-z

Siebe C, Arana-Salinas L, Abrams M (2005) Geology and radiocarbon ages of Tláloc, Tlacotenco, Cuauhtzin, Hijo del Cuauhtzin, Teuhtli, and Ocusacayo monogenetic volcanoes in the central part of the Sierra del Chichinautzin, México. J Volcanol Geotherm Res 141:225–243. https://doi.org/10.1016/j.jvolgeores.2004.10.009

Siebe C, Mendoza-Hernández PE, Juárez-Orozco S, Vázquez-Selem L, Cram-Heydrich S (2016) Consecuencias de la actividad volcánica del Xitle y el disturbio antrópico sobre las propiedades del suelo y la diversidad vegetal del Parque Ecológico de la Ciudad de México en el Ajusco medio. In: Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (conabio) y Secretaría del Medio Ambiente del Distrito Federal (sedema). La biodiversidad en la Ciudad de México. Conabio/Sedema, Mexico City

Singh SK, Reinoso E, Arroyo D, Ordaz M, Cruz-Atienza V, Pérez-Campos X, Iglesias A, Hjörleifsdóttir V (2018) Deadly intraslab Mexico earthquake of 19 September 2017 (M w 7.1): Ground motion and damage pattern in Mexico City. Seismol Res Lett 89(6):2193–2203

Solleiro-Rebolledo E, Straubinger M, Terhorst B, Sedov S, Ibarra G, Sánchez-Alaniz JI, Marmolejo E (2016) Paleosols beneath a lava flow in the southern basin of Mexico: The effect of heat on the paleopedological record. Catena 137:622–634

Straub SM, LaGatta AB, Martin-Del Pozzo AL, Langmuir CH (2008) Evidence from high-Ni olivines for a hybridized peridotite/pyroxenite source for orogenic andesites from the central Mexican Volcanic Belt. Geochem Geophys Geosyst 9(3):1–33

Ticar J, Komac B, Zorn M, Ferk M, Hrvatin M (2017) From urban geodiversity to geoheritage: the case of Ljubljana (Slovenia). Quaestiones Geographicae 36(3):37–50

Urrutia-Fucugauchi J, Goguitchaichvili A, Pérez-Cruz L, Morales J (2016) Archaeomagnetic dating of the eruption of Xitle Volcano, Basin of Mexico: Implications for the mesoamerican centers of Cuicuilco and Teotihuacan. Arqueología Iberoamericana 30:23–29

Van den Berg AE, Maas J, Verheij RA, Groenewegen PP (2010) Green space as a buffer between stressful life events and health. Soc Sci Med 70(8):1203–1210

Vereb V, van Wyk de Vries B, Guilbaud MN, Karatson D (2020) The urban geoheritage of Clermont-Ferrand : from inventory to management. Quaestiones Geographiceae 39(3):5–31. https://doi.org/10.2478/quageo-2020-0020

Waitz P, Wittich E (1910) Tubos de explosión en el Pedregal de San Angel. Bol Soc Geol Mex 7:169–186

Walker GPL (1993) Basaltic-volcano systems: Geological Society, London. Special Publications 76(1):3–38

Walker GPL (2009) The endogenous growth of pahoehoe lava lobes and morphology of lava-rise edges. In: Thordarson T, Self S, Larsen G, Rowland SK, Hoskuldsson A (eds) Studies in volcanology—the legacy of George Walker (Special Publications of IAVCEI No. 2). The Geol Soc: pp 17–32

Wittich E (1919) Los fenómenos microvolcánicos en el pedregal de San Ángel: Memorias de la Sociedad Científica Antonio Alzate. México 38:101–120

Wood CA (1980) Morphometric analysis of cinder cone degradation. J Volcanol Geotherm Res 8(2-4):137–160

World Heritage Committee (2007) Decisions adopted by 31st session of the World Heritage Committee. https://whc.unesco.org/en/list/1250/documents/. Accessed 17 December 2020

IUSS Working Group WRB (2015) World reference base for soil resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Res Rep No 106 FAO Rome, 203 p

Zambrano L, Rodríguez Palacios S, Pérez Escobedo M, Gil-Alarcón G, Camarena P, Lot A (2016) La Reserva Ecológica del Pedregal de San Ángel: Atlas de Riesgos. Mexico City, Mexico. Universidad Nacional Autónoma de México, Mexico City

Zambrano L, Cano-Santana Z, Wegier A, Arroyo-Lambaer D, Zúñiga-Vega JJ, Suárez A, Bouchain CR, Gual Sill F, Campo J, Ortega-Larrocea P, Fonseca A, Ramos AG, Coronel-Arellano H, Bonilla-Rodríguez M, Castillo A, Negrete-González M, Ramírez-Cruz GA, Pérez-López J, González Calderón B (2019) Evaluating socio-ecological interactions for the management of protected urban green spaces. Front Environ Sci 7:144