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The multiple values of urban geosites: El Arenal and Viaje a la Naturaleza parks in Mexico City

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Abstract

Urban geosites are an important resource for science, geoeducation and geotourism that may provide multiple benefits for local communities. The gigantic Mexico City is settled in a paleolake basin surrounded by Quaternary volcanic ranges. The SW corner of the city has spread over two of these ranges, Sierra Chichinautzin and the Sierra de las Cruces, leaving few outcrops in the dense urban network that are preserved in public parks. We present here the results of our study of the geological characteristics of two parks managed by local communities. We found surprisingly high geodiversity in these parks and their directly surrounding areas which, along with their accessibility, give them elevated geoeducation and geotourism values. This geodiversity is combined with biodiversity, creating a geo-bio-heritage that is, however, threatened by anthropic activities. We designed geopaths and, as a first approach to the communities, we organized field excursions along them which were highly successful in raising the knowledge and interest of local people on their geo-bio-heritage and also contributed to their awareness of anthropic threats that need to be addressed in order to achieve sustainable management for their conservation. Our project hence represents the first step of a strategy to promote the natural heritage to local communities, contribute to its conservation, and reduce the gap between science and society.

Key words: Geotrail, geopath, geoheritage, biodiversity, Sierra Chichinautzin.

Resumen

Los geositios urbanos son recursos importantes para la ciencia, la geoeducación y el geoturismo que pueden proporcionar múltiples beneficios a las comunidades locales. La gigantesca Ciudad de México está asentada en una cuenca de paleolago rodeada de cadenas volcánicas del Cuaternario. El sector suroeste de la ciudad se ha extendido sobre dos de estas sierras (Sierra Chichinautzin y Sierra de las Cruces), dejando pocos afloramientos que se conservan en los parques públicos. Presentamos aquí los resultados de nuestro estudio de las características geológicas de dos parques administrados por comunidades locales. Encontramos una geodiversidad sorprendentemente alta en estos parques y sus áreas circundantes que, junto con su accesibilidad, les confieren altos valores de geoeducación y geoturismo. Esta geodiversidad se combina con la biodiversidad, creando un geobiopatrimonio que, sin embargo, está amenazado por las actividades antrópicas. Diseñamos georutas y como un primer acercamiento a las comunidades locales, organizamos excursiones de campo a lo largo de ellas que que tuvieron mucho éxito en aumentar el conocimiento y el interés de la población local sobre su geobiopatrimonio y también contribuyeron a su conciencia sobre las amenazas antrópicas que deben abordarse para lograr una gestión sostenible de su conservación. Por lo tanto, nuestro proyecto representa la primera etapa de una estrategia para promover el patrimonio natural entre las comunidades locales, contribuir efectivamente en su conservación y reducir la brecha entre la ciencia y la sociedad.

Palabras clave: geosendero, ruta, geopatrimonio, biodiversidad, Sierra Chichinautzin.

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1. Introduction

The geoheritage is the ensemble of geological elements (rocks, minerals, fossils, landscapes, soils etc.) that are valuable for society. Geosites are places where some of those elements are present and can be appreciated very well, which can be local outcrops or the whole landscape. Geosites located in urban settings have specific characteristics (e.g., Reynard *et al.* 2017). In comparison to rural sites, urban geosites are typically smaller, more fragmented, and present some degree of degradation and loss due to the construction of infrastructures (e.g., Chan and Godsey 2016; Vereb *et al.* 2020). Nevertheless, they are of easy access by roads, tend to be safe and have a high density of population nearby, which increases their geoeducation and geotourism values (Brilha 2016). Moreover, they frequently coincide with the last remains of natural spots in urbanized areas and provide ecosystem services (Reverte *et al.* 2020; Guilbaud *et al.* 2021). In summary, despite their degraded nature, urban geosites are a precious resource for geoeducation and geotourism and also support biodiversity and environmental awareness in cities (e.g., Vegas and Díez-Herrero 2021).

Mexico City, one of the most densely populated areas in the world, faces volcanic important hazards due to its location within the Trans-Mexican Volcanic Belt, an active volcanic arc that crosses the country from west to east (e.g., Ferrari *et al.* 2012). The city is settled in a paleolake basin embedded in a diverse volcanic landscape, which consist of edifices of varied age, chemical composition, and morphology (Figure 1; Macías *et al.* 2012; Arce *et al.* 2013, 2019, 2020). To the north, there is Sierra Guadalupe which formed in the early-Miocene (Arce *et al.* 2020). To the east, there is the N-S Sierra Nevada that is a range of stratovolcanoes that include the currently erupting Popocatépetl, whose ash occasionally reaches the city (Macías *et al.* 2012). To the west, the Sierra de Las Cruces (SC) forms a N-S trending Pleistocene volcanic range (1-4 Ma) mostly made of eroded intermediate to silicic polygenetic volcanoes and related products (García-Palomo *et al.* 2008). To the south, the Sierra Chichinautzin Volcanic Field (SCVF) forms an E-W-trending range of over 300 young (< 1 Ma) monogenetic edifices (e.g., Arce *et al.* 2013; Sieron *et al.* 2023; Figure 1). These volcanic ranges have been declared conservation land ("suelo de conservación") in Mexico City because of their importance for ecosystem services such as aquifer recharge, biodiversity reservoir, climatic regulation, soil stabilization, agriculture production, recreation, and scenic and cultural values (Federal 2013).

Previous studies on Mexico City´s geoheritage have focused on Xitle volcano because it is the youngest dated volcano of the SCVF (1670 +/- 35 calibrated years before present; Siebe 2000) and hence one of the best preserved, and it fed an extensive lava field now covered by the city, therefore having a strong connection with the urban communities (Figure 1). Those studies have identified main geosites that have great scientific and cultural significance and provide numerous ecosystem services (Palacio and Guilbaud 2015; Guilbaud *et al.* 2021; Nieto-Torres *et al.* 2022). Nevertheless, many other public parks within the city also contain remains of this geoheritage, and the development of research projects in these parks could allow to advance the scientific knowledge while at the same time allow scientists to engage with citizens and stakeholders, with the aim to contribute to environmental conservation, increase people´s resilience to volcanic hazards, and reduce the science-society gap (Topp *et al.* 2018, 2020; Sarkki *et al.* 2020; Lièvre *et al.* 2022).

In this paper, we present the results of the study of two public parks located at close distance from Xitle: El Arenal and Viaje a la Naturaleza (Figure 1). These parks were selected for this investigation because we were approached specifically by park managers or local inhabitants who wished to obtain scientific information about the geological formations therein exposed, hence providing an opportunity to engage with local people. In addition, we identified a gap in the geological data available for these areas, as the few existing maps (Cervantes and Molinero 1995; Delgado *et al.* 1998) were either contradictory or not sufficiently precise to determine the nature and source of the geological elements that are exposed in these parks, which added scientific interest and value to the projects. Curiously, prior to our study, the local people believed that the volcanic products that are exposed at both parks (a sand dune at El Arenal and a blocky lava at Viaje a la Naturaleza) originated from the Xitle volcano, which was contested early-on by our observations. It seemed important for us to conduct detailed scientific investigations in these areas to be able to provide science-based information to the locals and park visitors. Finally, the existence of a significant contrast in the geographical and socio-economical context of these two parks made it interesting to combine results from both areas in this paper, which sets the foundation of a wider project about the perception of geoheritage in socially-distinct communities that is in progress.

First, we introduce both parks and their geographical and socio-economical contexts and then summarize the results of our geological studies on these parks and their immediately surrounding area which we define as our study areas. We also present preliminary data on the biodiversity at specific sites and provide a preliminary assessment of the main threats to the conservation of these natural elements which is based on direct field observations from our team and informal conversations that we had with the local people, including those that are in charge of the parks and others that were present during the excursions (see below). Next, we discuss the geodiversity that these parks hold, the direct relation that there is between this geodiversity and the biodiversity, and the potential scientific, geoeducational

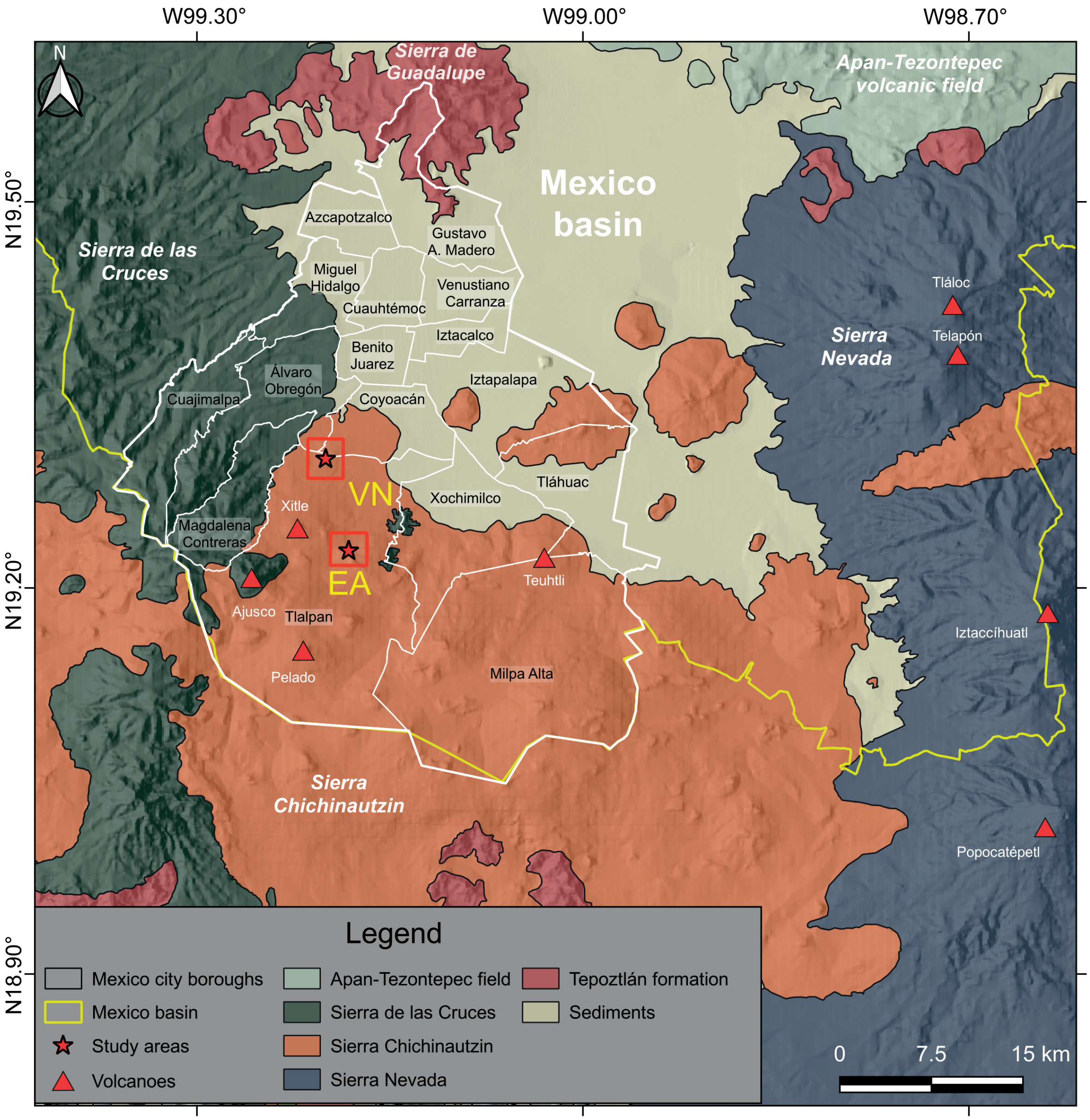

Figure 1. Geological map of the Mexico basin (modified from Arce *et al.* 2019) with the location of the city boroughs. Parks and associated study areas: VN: Viaje a la Naturaleza, EA: El Arenal. Shared relief digital element model used as background was built from Lidar data from INEGI (2000a).

and geotouristic values of the parks that we can derive from our scientific observations. We also present the itinerary of the field excursions that were planned and implemented, with the purpose of sharing our scientific results with the local community and raise their interest in the local geology. We observed that highlighting this often-unseen link between the geodiversity and biodiversity drives the community´s interest in their conservation. We acknowledge that the inferences we make throughout the text about people’s perceptions on geoheritage remain to be confirmed and expanded through the conduction of surveys by specialists from the social and political science disciplines.

2.General characteristics of the parks

The general characteristics of the studied parks are summarized in Table 1. Both are located in the Tlalpan borough (“alcaldía”) that forms a N-S stretch across the SW margin of the basin. This borough extends from a highly-urbanized lower-altitude area in the north (ca. 2300 masl) to the higher-altitude (>2500 masl) less densely-populated conservation lands of the SCVF in the south (Figure 2a). The El Arenal park is located in the Magdalena-Petlacalco neighborhood at the margin of the densely inhabited area, within the conservation lands (Figure 2a).

Table 1. General characteristics of the parks.

Urban park	El Arenal	Viaje a la Naturaleza
Meaning of name	Sandy area	Trip to Nature
Park area	12,500 m^2 (4)	49,339 m^2 (3)
Neighborhood	La Magdalena Petlacalco	Jardines en la Montaña
Total population	2445 (1)	4131 (1)
Degree of margination	Very high (1)	Very low (1)
Altitude	2730-2800 masl (4)	2340-2420 masl (3)
Accessibility	Accessible to public at specific hours	Only accessible to inhabitants and their visitors
Legal status	Fragmented green urban area (“área verde urbana fragmentada”) (2)	Restoration and environmental conservation community area (“área de Restauración y Conservación Ambiental Comunitaria”) (2)

Source: 1: Coordination of territorial development planning, from INEGI (2000b); 2: information given by community leaders. 3) document retrieved from the internet. 4. (Villalba, 2023).

The Viaje a la Naturaleza park is located 8 km directly to the north (Figure 2a) within the Jardines en la Montaña neighborhood near “Periferico Sur”, a mayor avenue of the city.

El Arenal park has been known for decades by the population of the south of Mexico City where families could go to enjoy their Sunday but where, equally, locals would extract material for construction. In 2015, the park was fenced and established as an (unofficial) ecotouristic park (Figure 2b) that is managed by the local community through its communal land (“ejido”) representatives and where extraction of the material is prohibited. The park is mentioned in numerous local blogs and internet pages. The Viaje a la Naturaleza park (Figure 2c) that is located inside a privileged borough started to be managed in 2020, through a specially created committee (“comité de ecología”) within a local association of neighbors (“asociación de colonos”) (Urroz 2022). It was originally used as a dump and considered unsafe by the borough inhabitants, but has being converted into a pleasant park thanks to actions by the community (Urroz 2022).

Managers of both parks are actively working on conserving and restoring their beloved area. The Arenal park is working on its formal designation as an ecotouristic park, though an active collaboration with SECTUR which is the city´s secretary of tourism, while the Viaje a la Naturaleza park is seeking its designation as an urban woodland with an environmental value (“área de valor ambiental en categoria de bosque urbano”). Leaders of both projects are interested in acquiring technical, scientific data that could consolidate their proposals, which is part of the objectives of this study.

3. Methodology

For each case, we defined a study area that includes the park of interest for both communities, and an area with a radius of about 1 km around the park so that the study area was large enough to allow to understand the geological setting of the park. Geological methods included several weeks of field work (with cartography, stratigraphic correlations and sampling) and sample analysis (thin sections of representative samples from each geological formation were made, in addition to granulometry and componentry studies for tephra deposits and radiocarbon dating of paleosols and charcoal). The examination of older aerial photographs was of particular interest to map the extent of the products and describe their characteristics prior to extensive urbanization. This was particularly useful for the Viaje a la Naturaleza study area which is the most densely urbanized. The photographs also revealed changes in land use and morphology during the last 40-50 yrs. The entire dataset is contained in the theses of Villalba (2023) and Rodriguez Osnaya (2024). Here we focus on summarizing their results, describing some elements of geodiversity.

Biodiversity was described at specific sites, making a list of the dominant plant species observed and paying particular attention to its relationship with geodiversity and the type of soil on which it is found. The threats to geological and biological elements were identified during the fieldwork in each study area and complemented with what the community itself has identified over time and which has caused them trouble to address, which was obtained from informal conversations with locals and park managers.

In the following, we describe successively at each park and study area elements of geodiversity, pedodiversity, biodiversity and identified threats. At the end of the paper we describe the geopaths that were planned, paying special attention to identify those sites that would give the possibility to describe the close relationship of geo and biodiversity, the soil and the ecological function they fulfill, to emphasize the threats that these sites are

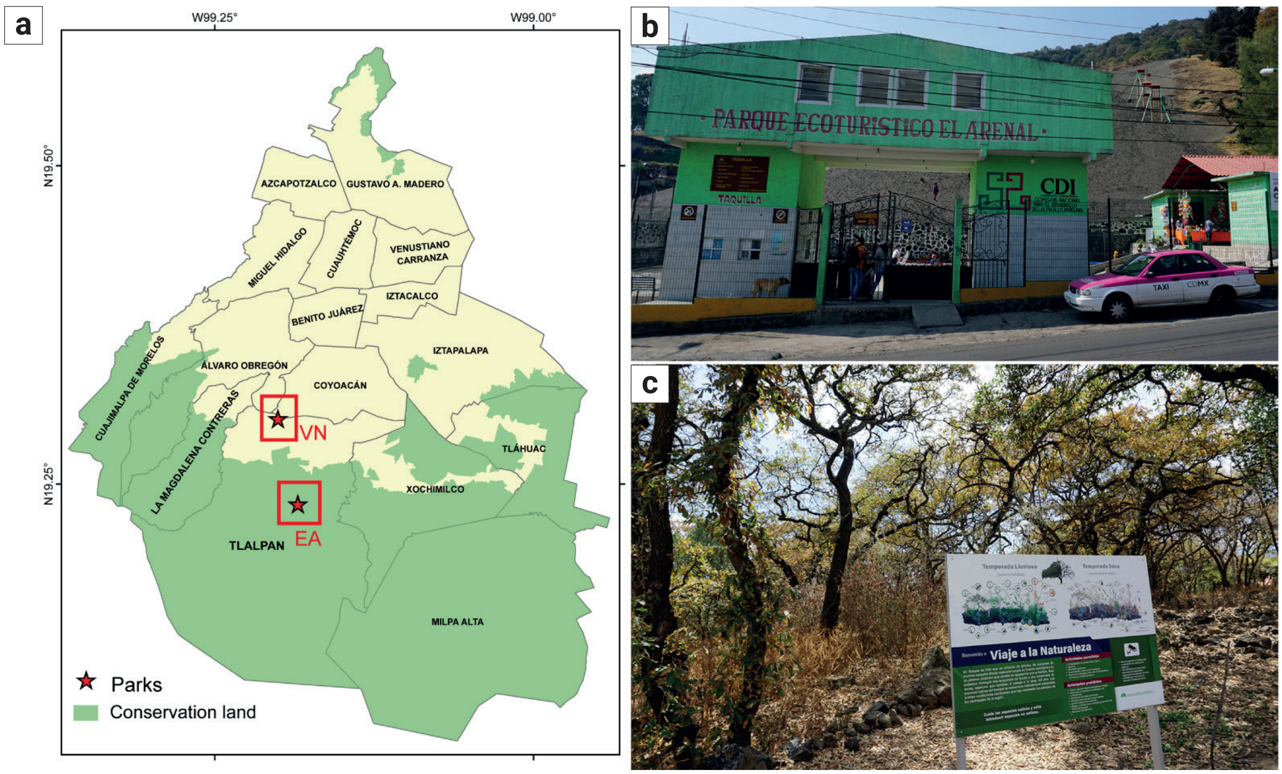

Figure 2. a. Location of both parks and associated study areas in Mexico City map. VN: Viaje a la Naturaleza park, EA: El Arenal park. Red rectangles: study areas. Background map elaborated with shape files for Mexico City uploaded from: https://datos.cdmx.gob.mx/. b. El Arenal park: building constructed at the entrance of the park (photo taken in April 2021). c. Viaje a la Naturaleza park: Interpretation panel about seasonal changes in vegetation located near the botanical garden; endemic oak forest in background (photo taken in March 2022).

vulnerable to, in addition to identifying sites with panoramic views over the volcanic landscape that allow to highlight the fact of living in a volcanic area that represent a risk.

4. Results

4.1. El Arenal park and study area

Despite its small extent (12 km^2) the El Arenal study area contains diverse types of volcanic products and structures (Figure 3). The El Arenal park consists of a large amount of loose black sand deposited on a slope that forms a dune-like structure (Figure 4a). Our study indicates that this sand is made of volcanic ash hereafter called Arenal ash that was deposited over an older dome (Cerro Magdalena, Figure 4c) and extends down to a 1 km in distance, beyond which it is covered by the Xitle lavas (Figure 3). Directly to the SE of the dome lies a young 110 m-high scoria cone (Yololica, Figures 4d and 4e) that fed lavas which surrounded the dome and produced well-exposed fallout deposits (Figure 4b). At the SE prolongation of the cone we also mapped hummocks of spatter and lava that may be part of a small debris avalanche deposit or may be pieces of the cone rafted on top of lava (Figure 4). Furthermore, we found lithic-rich pumice fallout deposits from a mayor eruption of Popocatépetl stratovolcano that forms a prominent stratigraphic marker across the SCVF (the so-called Tutti-Frutti pumice: Siebe *et al.* 2004; Sosa-Ceballos *et al.* 2012; Guilbaud *et al.* 2015) and an 85 m-thick fallout sequence from Pelado volcano, a monogenetic shield located 10 km to the south (Figure 4b). These tephra deposits are intercalated by organic paleosols (Figure 4b) dated by the radiocarbon method.

This small area is notably compositionally diverse. Products range from basaltic (Xitle) through basaltic andesitic (Yololica) and andesitic (Arenal ash, Pelado, Tutti-Frutti), up to dacitic (Cerro Magdalena). The Arenal ash itself is surprisingly diverse in its components. It includes diverse types of variably vesiculated juvenile components (tachylite, sideromelane, dense) mixed with loose crystals (pyroxene, olivine, quartz and plagioclase) and lithic components (altered pumiceous and dense clasts). A thorough stratigraphic, textural, petrographic and geochemical study suggests that it is composed of Pelado fallout ash mixed

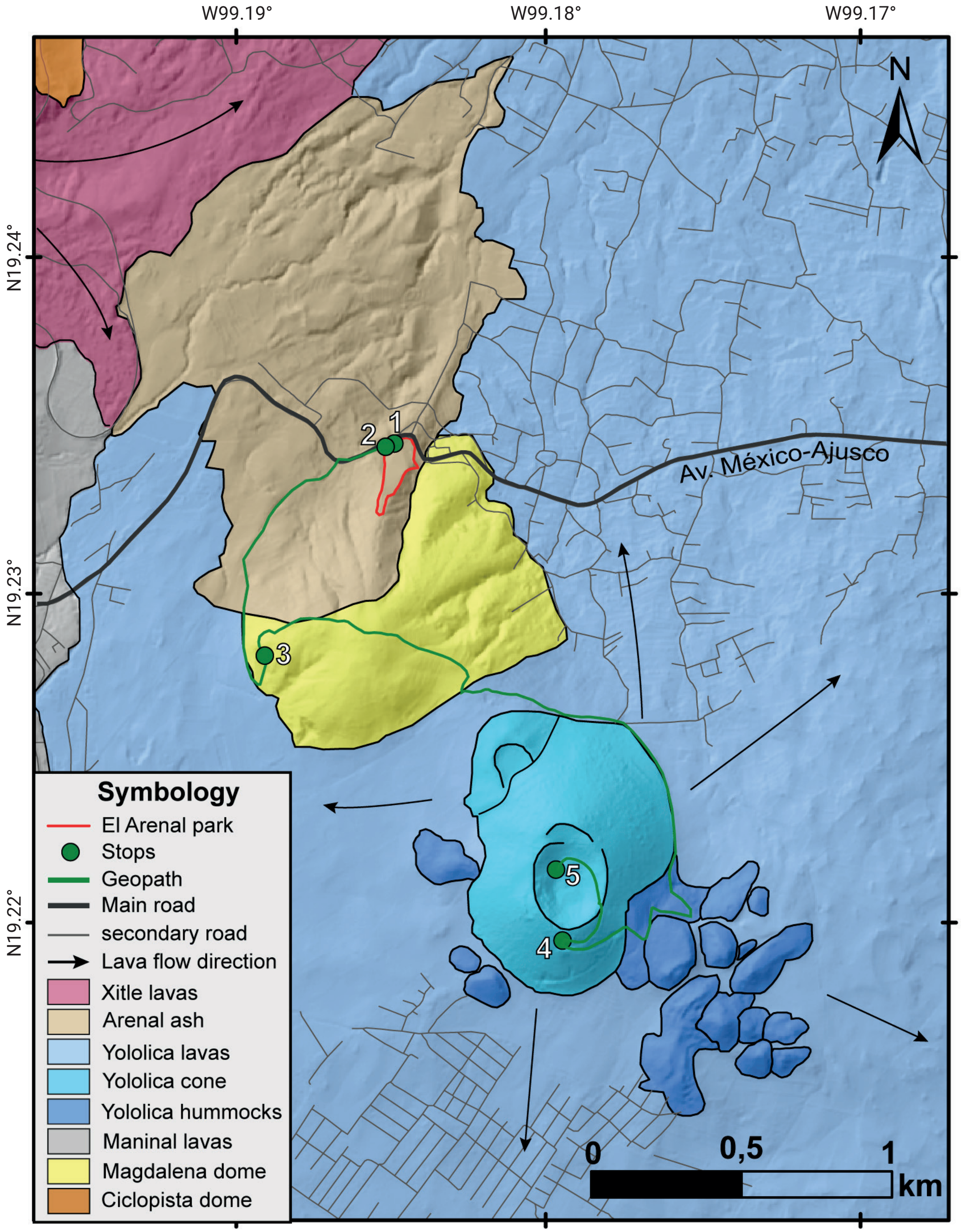

Figure 3. Geological map of El Arenal study area with the geopath itinerary and the incipient road network. Shared relief digital element model used as background was built from Lidar data from INEGI (2011).

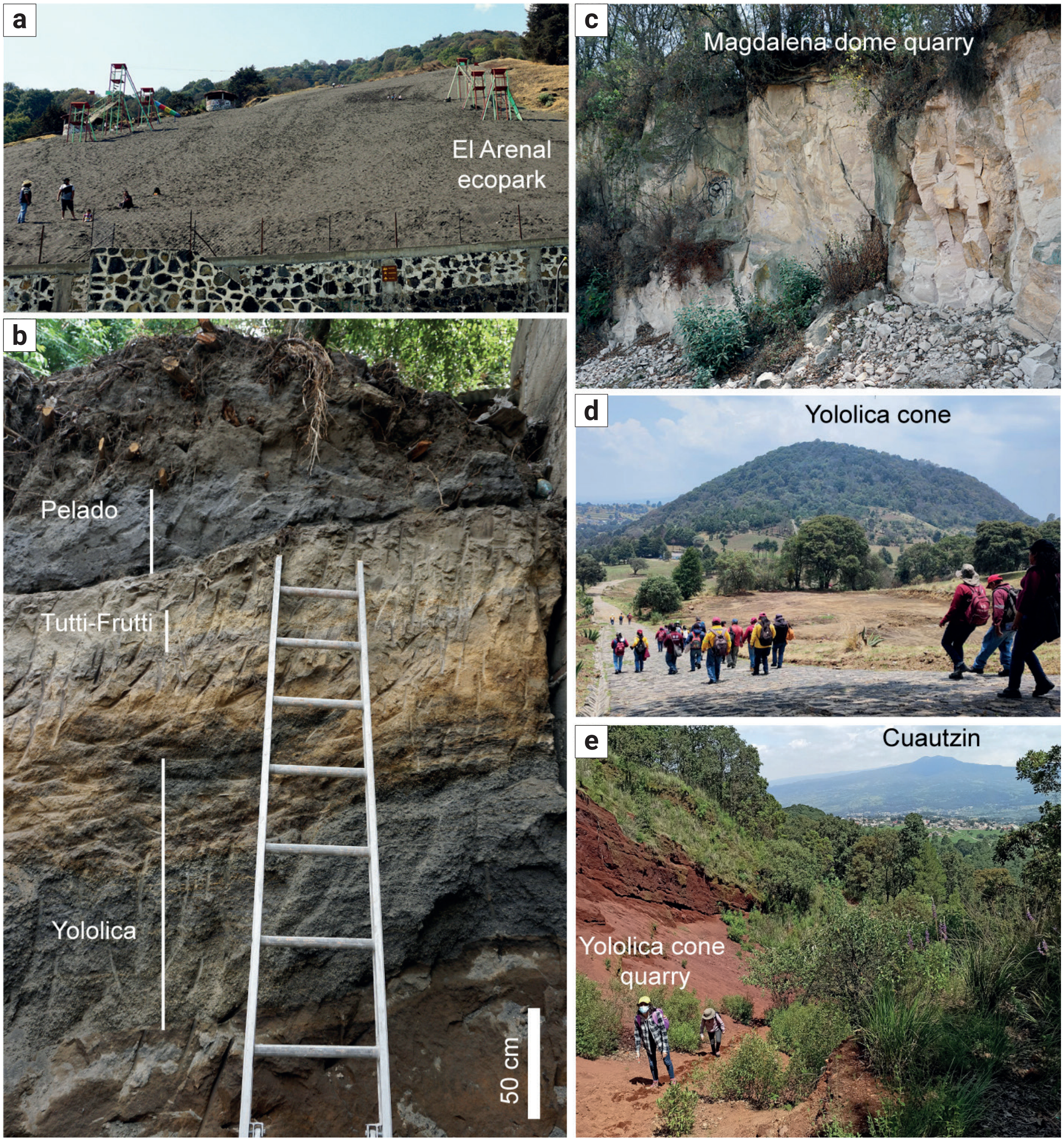

Figure 4. Geodiversity in El Arenal study area. a. View of El Arenal sand dune from park entrance (stop 1 on geopath). b. Sequence of tephra fallout deposits from local volcanoes intercalated with paleosols (stop 2 on geopath). c. Quarry into Cerro Magdalena dacitic dome (stop 3 on geopath; April 2021). d. View on Yololica cone from the southern slopes of Cerro Magdalena (excursion with "brigadistas"; May 2023). E. View of quarry into Yololica cone in foreground and Cuautzin shield volcano in background (stop 4 on geopath; September 2021).

with the Tutti-Frutti pumice (Villalba, 2023). This mixing likely occurred during dust storms that closely followed the Pelado eruption, when the ash was loose and vegetation was absent. Nevertheless, the dune is still actively eroding mostly due to anthropic activities that lead to the destruction of the slight ash induration and incipient vegetation cover on a 3 to 4 cm-thick organic horizon.

Volcanoes of this area are also diverse in age and range from about 1 Ma for the Cerro Magdalena dome, through 22,000 calibrated years before present (cal yrs BP) for the Yololica cone (Villalba, 2023), 16,870 cal yrs BP for the Tutti-Frutti horizon (Sosa-Ceballos *et al.* 2012), 12,000 cal yrs BP for the Pelado eruption (Siebe *et al.* 2004; Guilbaud *et al.* 2022) and 1700 cal yrs BP for Xitle (Siebe 2000).

Because pedodiversity reflects the combination of specific soil-forming factors and that, among these, the lithology (Figure 3), time for soil formation, and relief vary across the area, we expect the formation of different types of soils with different characteristics. The soil profiles were not formally described at each site, but we observed differences in the depth of development and in the color of the soil horizons, so that we can expect a complex soil chronosequence such as that described by Peña-Ramírez *et al.* (2015) for volcanic soils in the Chichinautzin.

Table 2 present a list of conspicuous vegetation species at specific sites across the study area (locations on Figure 3). It results that the vegetation in the area corresponds to an assembly of native oak-pine-arbutus forest of *Quercus deserticola* along with other species. Ailes *(Alnus acuminatae)* are only present in the upper inner slopes of the Yololilca crater, whereas grassland dominate in its center. Pictures of representative specimens in all the studied areas are presented on Figure 5.

In terms of human activities that threaten geo- and biodiversity, we have identified an accelerated process of land use change, dominated by urbanization, which has induced deforestation, a reduction in the presence of native wildlife, an increase in exotic species of flora and fauna, and especially poor solid waste management, since garbage accumulates across the entire areas, especially where there are hollows, depressions, and caves (Villalba, 2023). People consider these to be disposal sites due to a lack of perception of the value of geo-biodiversity. Tree growth is also impacted by parasites such as mistletoe (Table 2) that proliferate due to the recent rise in temperatures caused by human activities that accelerates climate change.

4.2. Viaje a la Naturaleza park and study area

The Viaje a la Naturaleza study area is of similar size as El Arenal study area (10 km^2) and also includes a wide range of

Table 2. Vegetation species in El Arenal study area, as observed at stops along the geopath (Figure 3). The listed invasive and exotic species represent anthropogenic threats. Species of particular interest are shown in bold.

Geopath stop	El Arenal park and section nearby (stops 1 and 2)	Cerro Magdalena quarry (stop 3)	Yololica slopes (stop 4)	Yololica crater (stop 5)
Native tree species	***Quercus deserticola*** (white oak) *Q. rugosa* *Pinus montezumae* *Arbutus xalapensis* (arbutus) *Buddleja cordata* (tepozán) *Prunus serotina* subsp. *capuli* *Yucca elephantipes* *Cupressus lusitanica* (cedar) *Fraxinus uhdei* (ash tree)	***Q. deserticola*** *P. ayacahuite* *A. xalapensis* (arbutus) *B. cordata* *Pr. serotina* subsp. *capulí*	***Q. deserticola*** *P. leiophylla* *P. teocote* *A. xalapensis* ***Alnus acuminata*** *Pr. serotina* subsp. *Capulí* *B. microphylla* *B. cordata*	***Q. deserticola*** ***Q. rugosa*** *P. ayacahuite* *P. hartwegii* *P. teocote* *P. montezumae* *P. leiophylla* *A. xalapensis* ***A. acuminata***
Native herbaceous	*Salvia mexicana* *Salvia elegans* *Lopezia racemosa* *Symphoricarpos microphyllus* *Loeselia mexicana* *Sedum oxypetalum*	*Muhlembergia robusta* *Penstemon campanulatus* *Agave salmiana* *Vervesina virgata* *Eryngium* sp. *S. mexicana*	***M. macroura*** ***M. rigens*** *Castilleja tenuiflora*	***M. macroura*** ***M. rigens*** *Senecio cinerarioides* *Castilleja tenuiflora* *Vervesina virgata*
Exotic and invasive species	*Casuarina equisetifolia Rubus liebmannii* (bramble) *Rumex obtusifolius (lengua de vaca)* *Tropaeolus majus* (cress) *Galinsoga parviflora* *Bidens odorata* ***Pennisetum clandestinum*** (Kikuyo grass) *Medicago polymorpha*	*Cladocolea* (mistletoe)	*Phoradendron* sp. (mistletoe)	

Figure 5. Photographs of representative specimens of the dominant plant species in the studied areas. a) Native *Quercus deserticola*, Jardines en la Montaña; b) native *Pinus teocote*, Yololica cráter; c) native *Arbutus xalapensis*, Yololica cráter; d) exotic invasive *Eucaliptus camadulensis*, Bosque de Tlalpan; e) native fern *Cheilanthes bonariensis*, Tlalpan Xeropitic scrub; f) native *Salvia elegans*, Jardines en la Montaña; g) native *Salvia mexicana*; El Arenal; h) native *Verbesina virgata* Yololica cráter; i) *Muhlembergia robusta*, Magdalena Quarry.

volcanic deposits (Figure 6). This area encloses several major roads (Periferico Sur, Boulevard Picacho-Ajusco) and is extensively urbanized, except from the Bosque de Tlalpan which is a 2.53 km^2 park in the south of the study area that was declared as a natural protected area ("Area Natural Protegida" or ANP). This park preserves extensive outcrops of the geological formations that were valuable for mapping and sampling. Some geoheritage elements of this park were described by Palacio and Guilbaud (2015).

The Viaje a la Naturaleza park consists of a 400 m-long, 150 m-wide and <50 m-high elongated ridge with a curved shape (Figure 6). This ridge is covered by a dense native oak forest (Quercetum) that grows on a hummocky, blocky lava made of large (m-size), poorly-vesicular, angular blocks with altered surfaces, and covered by an up to 1 m-thick developed soil (Figure 7A). Locally, a thin (<10 cm) layer of altered pumice clasts and lithics outcrops on top of the soil.

Our study of the surrounding area indicates that the blocky lava exposed in the park and which we hence named "Viaje de la Naturaleza", outcrops as topographically-elevated areas or ridges that were surrounded by the young Xitle lavas flows (in green on Figure 6), which are features named in the scientific literature as Kipukas, a term from the Hawaiian language (Macdonald and Huggard 1951). The Xitle lavas occur as several units with overlapping contacts in the study area (dark brown, orange to red colors on Figure 6) that vary in surface morphology from sheet to hummocky pāhoehoe for the units 1, 2, and 4 (Figure 7b), to channelized ʻA'ā for unit 3 (Figure 7c).

We also identified another type of Kipukas that mostly outcrops in two ca. 100 m-high hills located in the study area (Zacatépetl and Zacayuca, blue on Figure 6). Those present a thick cover of clayey soils that is locally overlaid by the same pumice layer detected at Viaje a la Naturaleza, which is fresher, better exposed and reaches a maximum thickness of 3 m in the Bosque de Tlalpan (Palacio and Guilbaud 2015; Arce *et al.* 2017). At the lower part of these hills, several-m large, rounded crystal-rich blocks outcrop (Figure 7d); we interpret these blocks as the inner part of deeply eroded domes. These kipukas are surrounded by young sedimentary deposits (Figure 6) that possibly formed by erosion and re-deposition of their covering soils. As for the other park, products display a great variation in chemical composition from basaltic (Xitle), through basaltic andesitic (Viaje a la Naturaleza Kipuka), to dacitic (Zacayuca Kipuka). In terms of ages, in addition to the Xitle, only the altered pumice layer has been dated, with an age of about 30 ka (Arce *et al.* 2017). The origin of such product is poorly defined but, based on its dacitic composition, it probably emitted by a volcano of the Sierra de Las Cruces (Arce *et al.* 2017).

In terms of pedodiversity, the Kipukas, which are islands surrounded by much younger lavas, are excellent sites to show differences in soil development and ecological succession processes. The older Kipukas with more developed, several m-thick soils contrast with the younger Xitle lavas covered partially by very shallow stony Leptosols, providing a striking visual contrast. Interestingly an early English definition of the Hawaiian term was "an oasis of rich soil amid a lava flow" (Reinecke and Tokimasa 1934), which could apply here.

Tables 3 and 4 present a preliminary list of conspicuous vegetation species in Jardines de la Montaña neighborood and Bosque de Tlalpan Park, respectively, with some pictures in Figure 5. The distribution of the species reflects the distinct soil types with some impacts from management practices. In Jardines en la Montaña (Table 3), the Viaje a la Naturaleza park (Figure 6) is dominated by a native monospecific (1-species) 3 to 6 m oak forest (quercetum) of *Quercus deserticola* (Figure 7a), where as, because of gardening, the Xitle lavas that outcrop in the rest of the neighborood are covered mostly by ornamental exotic species with few native specimen (Figure 7b).

In comparison, at Bosque de Tlalpan Park (Table 4), the Zacayuca Kipuka is entirely covered by an artificial mixed forest with invasive species (Figure 7d) that results from reforestation (Lenz 2010). In contrast, the Xitle aa lavas show a particular native xeric scrub vegetation on shallow stony Leptosols (Figure 7c). Those young lava surfaces support high biodiversity due to the complex geomorphology that offers a variety of microenvironments with differential conditions of temperature, light and humidity (e.g., Guilbaud *et al.* 2021) (Table 4).

The threats identified by the caretakers of the Viaje a la Naturaleza park (information obtained by conversations) are fires during the dry season, tree pests such as mistletoe, the presence of exotic species that have a high dispersal power such as *Pennisetum clandestinum*, and abandoned dogs and cats. They also mention the inappropriate behavior of people who visit the area to walk their dogs and leave excrement and use the site to dispose of garbage. Another widespread threat is that the forest is identified as an unsafe area because it is dark and there is no visibility, which often leads to requests to remove it. This pressure for a change in land use has led the community to request government authorities to declare the area an area of environmental value in the urban forest category.

5. Discussion

Our study reveals that the two parks: El Arenal and Viaje en la Naturaleza and their surrounding areas are relevant geoheritage areas that can be used to raise awareness in the local communities. In the following discussion we demonstrate the diverse values that these areas hold (based on our geological and biological results) and show the initiatives that were implemented to transfer this

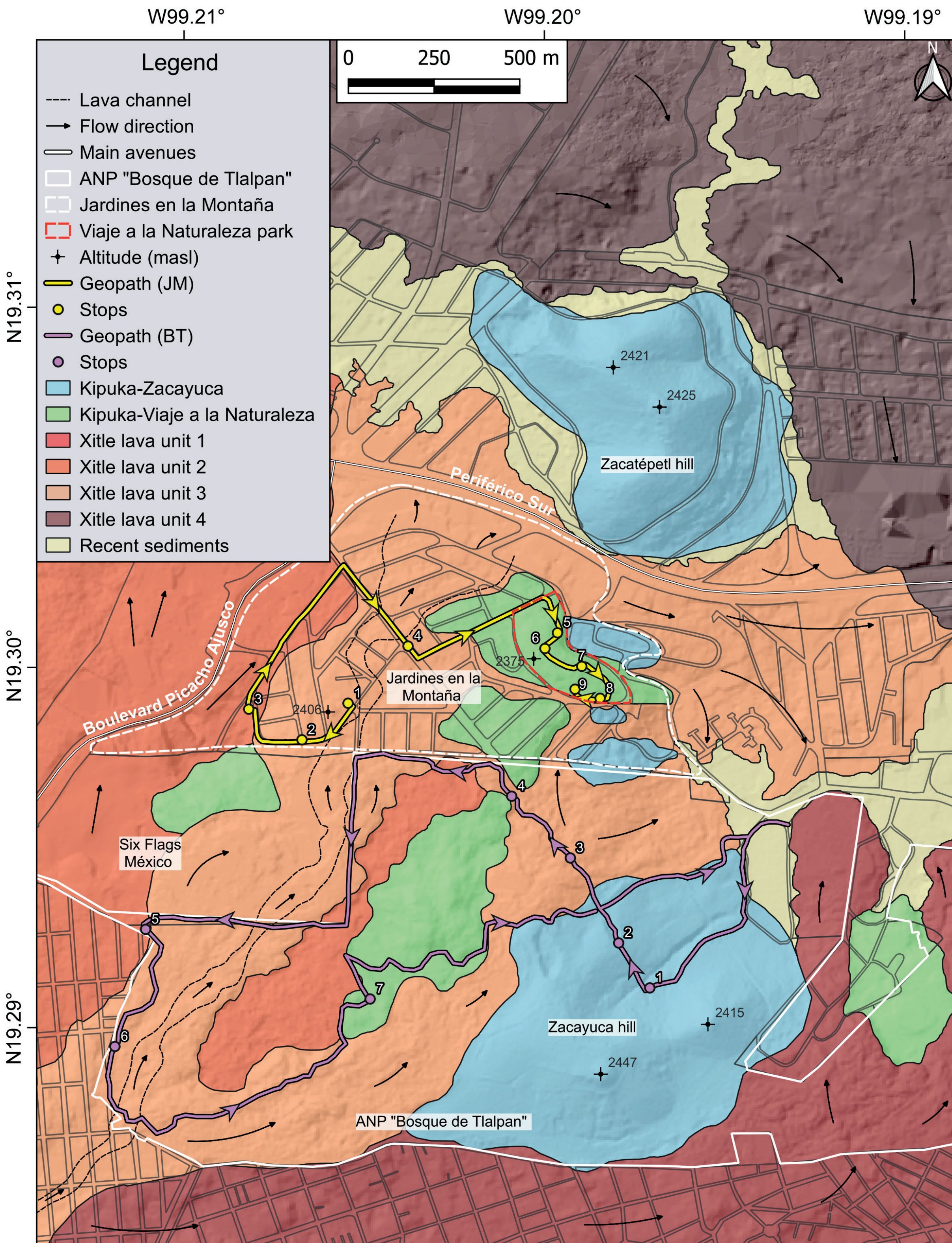

Figure 6. Geological map of Viaje a la Naturaleza study area with the road network and the location of geopaths in Jardines en la Montaña (JM) residential area (north) and Bosque de Tlalpan (BT) protected natural area (ANP, south). Shared relief digital element model used as background was built from Lidar data from INEGI (2011). Note areas with high errors coincide with large infrastructure.

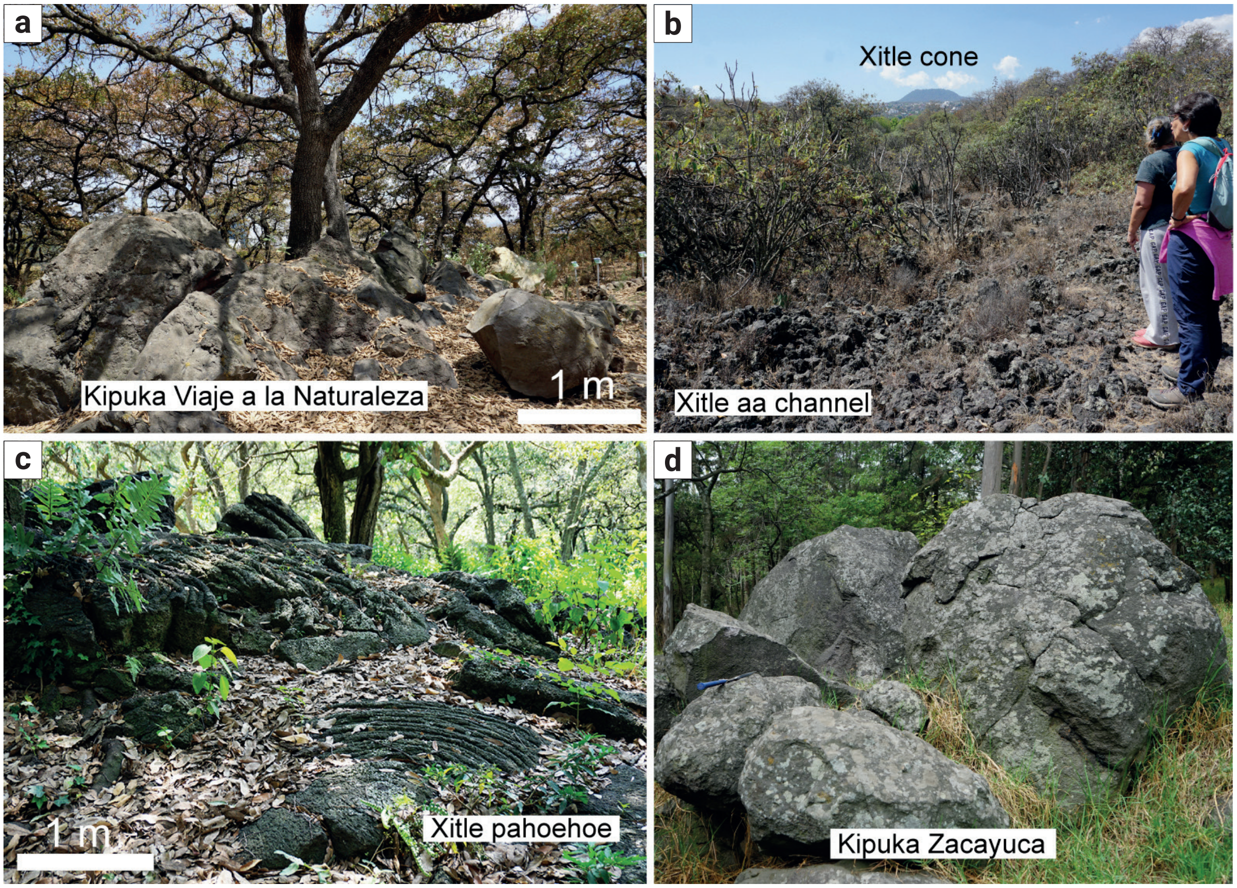

Figure 7. Geodiversity in the Viaje a la Naturaleza study area. a. Viaje a la Naturaleza park: Rocky surface made of altered andesitic blocks (Viaje a la Naturaleza Kipuka, stop 6 on yellow geopath on Figure 6). b. Pahoehoe-type Xitle lava in Sorata park, Jardines en la Montaña (stop 3 on yellow geopath on Figure 6). c. Bosque de Tlalpan: Xitle lava channel in the foreground and cone at the background (stop 6 on blue geopath on Figure 6). d. Bosque de Tlalpan: large rounded rhyolitic blocks at the base of Zacayuca Kipuka (start point of blue geopath on Figure 5).

knowledge to the park managers and local residents to promote its integration into the conservation plans of the parks. We also highlight the need to describe and address the drivers of the threats that put conservation at risk, many of which may have to do with the low perception and value given to geo-biodiversity. This work is a first step to contribute to change that perception.

5.1. Geodiversity value of the study areas

Geodiversity can be simply defined as "the diversity of geological features" (Gray 2021) or, more comprehensively, as "the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, physical processes) and soil features" (Gray 2004). In this regard, the study areas present significant geodiversity as they contain a variety of rock types (basaltic to dacitic, igneous to sedimentary) and associated minerals, which constitute different landforms (dunes, scoria cones, lava domes, hummocky avalanche deposits, pahoehoe to aa lava flows) produced by distinct processes (volcanic, sedimentary, erosional, depositional). We add that, although these aspects are only briefly addressed in this paper, the sites along the geopaths also provide the opportunity to observe a wide diversity of soil features, related with variations in the lithology (lava, ash), age (recent to Pleistocene) of the substrate and relief (slope variations).

This great geodiversity is a consequence of the location of both study areas where the SCVF overlaps the Sierra de las Cruces (Figure 1; Arce *et al.* 2019). In this area, older, more evolved volcanoes of the Sierra de las Cruces were partly covered and locally surrounded by younger, more mafic lavas from Sierra Chichinautzin (Xitle and Yololica), hence cuasing a significant diversity in the volcanic formation that are exposed in this area. We note that the older volcanics remain to be studied in detail, being potentially a valuable record of the volcanism in the early Pleistocene in this region. There is a larger amount of data on the younger volcanics, yet, prior to this work, there was little information on the Yololica volcano. Our study of El Arenal sand allows to revise the origin of the ash and provide

Table 3. Vegetation species at stops located along the geopath of Jardines en la Montaña area. The listed invasive and exotic species represent anthropogenic threats. Dominant species are in bold.

Geopath stop	Viaje a la naturaleza park (stop 6) Quercetum	Paseo del pedregal street reservation (“camellón”) (stop 4) Urban park	Sorata street border (stop 2) Urban park	Sorata park (stop 3): Mixed forest
Native tree species	***Q. deserticola*** *Eysenhardtia polystachya* (palo dulce)		*Q. deserticola* *Q. rugosa* *B. cordata* *Yucca elephantipes* (izote)	*Q. deserticola* *Q. rugosa* *E. polystachya* *Buddleja cordata* *Cupressus lusitanica*
Native herbaceous	*Salvia Mexicana* *Iresine* sp. *Funastrum* sp. *Aegopogon tenellus* *Cissus sicyoides*		*Phlebodium aureolatum* *Cheilanthes bonariensis* *Bidens odorata* *Peperomia campylotropa* *Dicliotera peduncularis* *Piqueria trinervia*	*Tillandsia recurvata* *Plumbago pulchella* *Drymaria affin laxiflora* *Pseudognaphalium* sp. *Peperomia campylotropa* *Aegopogon tenellus* *Piqueria trinervia* *Echeandia mexicana* *Commelina* sp. *Pellaea cordifolia* *Cheilanthes affin myriophylla*
Exotic and invasive species	*Jacaranda mimosifolia* *Sida rombifolia* *Brumus* sp. *Setaria* sp.	*Fraxinus uhdei* *J. mimosifolia* *Eucaliptus camadulensis* *Bougainvillea spectabilis* *Prunus persica* *Schinus terebinthifolius* (brazilian pepper) *Platycladus orientalis* (lemon cedar) *Cupressus sempervivens* (italian cypress) *Aptenia cordata* *Pennisetum clandestinum*	*F. uhdei* *P. persica* *Ficus carica* (fig) *S. terebinthifolius* *Solanum pseudocapsicum* *P. clandestinum* *Phytolaca icosandra* *Lepidium virginicum* *Oenothera kuntheana* *Passiflora* sp. *Rumex crispus* *Stevia* sp. *Agapanthus* sp.	*J. mimosifolia* *F. uhdei* *E. camadulensis* *P. clandestinum*

valuable information about processes of ash remobilization in monogenetic settings (Villalba 2023). In addition, although the eruptive chronology of the Xitle volcano is relatively well known (Delgado *et al.* 1998; Siebe 2000), there is no detailed description of the Xitle lavas morphologies, which is well exposed in the studied sites and present marked variations. The studied sites are hence potentially valuable for scientific purposes, although detailed research remains to be conducted.

5.2. Pedo- and biodiversity of the sites and links to geodiversity

As shown above, the parental materials on which the soils and vegetation have developed vary widely in the two study areas (sand dunes, scoria cones, lava domes, pahoehoe, aa to blocky lavas). Nevertheless, the same type of vegetation has developed on them, which is a forest dominated by a specific oak species (*Quercus deserticola*) with some variations in its association with pines, other oak and/or arbutus species. Apparently, factors such as slope orientation and altitude predominantly control the climax stage of the vegetation (mature stage of the ecological succession), which is a pattern that we also observed in the Xitle vent area, although, strangely, the *Quercus deserticola* species was not observed at the Xitle cone (Guilbaud *et al.* 2021). Nonetheless, the Yololica cone crater, such as Xitle's crater, is dominated by unique grassland species which can be

Table 4. Vegetation species in the two main types of geological units located in Bosque de Tlalpan park. The listed invasive and exotic species represent anthropogenic threats. Dominant species are in bold.

Geological unit	**Zacayuca Kipuka**	**Xitle lavas**
	Artificial mixed forest	**Xeric scrub**
Native tree species		***Q. deserticola*** ***Q. rugosa*** *B. cordata* *Y. elephantipes*
Native herbaceous		*Pittocaulon praecox* (palo loco) *Agave salmiana* *Opuntia* spp. *Mammillaria magnimamma* *Sedum oxypetalum* *Echeverria gibbiflora* *E. polystachia* *Ch. myriophylla Myriopteris aurea,* *Pellea* spp. *Conopholis americana* (elote de oso)
Exotic and invasive species	*B. spectabilis* *Schinus molle* *C. sempervivens* *P. clandestinum* *Leonotis nepetifolia* *Ricinus communis* *Agapanthus* sp.	

explained by conditions of high insolation and fertile loose ashes (Tisdale *et al.* 1965; Guilbaud *et al.* 2021). A notable exception of this forest-dominated vegetation is the young Xitle aa-type lavas whose extremely rough rocky surface with very shallow and stony soil cover is overgrown by a xeric scrub (Figure 7c). This scrub type has biological adaptations to obtain minerals and resources in a short period of time (Rivera *et al.* 2019) and predominates in lower-altitude areas of the Xitle lava field (e.g. Guilbaud *et al.* 2021). Elsewhere, soil formation processes over tens of thousands of years on scoria or lava has allowed the development of a mature forest of native *Quercus deserticola* that is adapted to the dry highlands of the Trans-Mexican Volcanic Belt (Rodríguez-Gómez *et al.* 2018).

5.3. Threats to natural elements and causes

The threats to geodiversity are diverse and almost always related to human activities that begin with land use change with the intention of meeting the needs of a growing population (Setälä 2014). This change in land use is more evident at El Arenal park, wich is located in a rural area undergoing continuous urban development (Villalba 2023), as opposed to the Viaje a la Naturaleza park that is surrounded by an already urbanized area and where the community is trying to conserve the last remains of original spaces. Prominent hills (Kipukas) in this area were strongly impacted by reforestation practices which were linked to the establishment of a paper factory in the area in 1845 (Lenz 2010) and resulted in the existence of woods dominated by usually unhealthy and vulnerable exotic species.

Threats can be reduced or managed if we are careful about our relationship with the environment and if we are aware of our vulnerability to existing threats, which in fact put the lives of all living beings at risk. Measures can be taken to ensure that hazards do not turn into disasters and the first step is to be sensitive and aware of the need for the conservation of geodiversity and the biodiversity it supports, both in rural and urban areas.

The causes of threats are varied and complex and are generally very similar in all natural areas, whether protected or unprotected (Zambrano *et al.* 2016; CONABIO 2016) and they often have to do with the way we identify ourselves as part of nature, and how we value the remaining natural spaces. This is why this type of multidisciplinary work, both among academics from different areas and sectors of society, is necessary, as it contributes to change our perceptions and more people are aware of the great value of conserving the local geo-biodiversity. Do we need to conserve geobiodiversity or does geobiodiversity conserves us? (Quinn 1991).

5.4. Geoeducation and geotourism values

Young volcanic landforms are common touristic attractions due to their aesthetic landscapes and because they provide opportunities for geoeducation on volcanic processes and related hazards and risks, which is well developed in national parks and geoparks worldwide (Erfut-Cooper 2011). Nevertheless, active volcanoes, especially those in eruption, are areas with significant risks for the visitors (Heggie 2009; Erfut-Cooper 2011). In comparison, monogenetic fields can provide an easy and safe access to a wide range of smaller, "human-scale", inactive volcanic structures that can be used to convey key information about volcanic processes (Moufti *et al.* 2015; Khalaf *et al.* 2019). Geotourism (sustainable geology-based tourism, Dowling 2013) can be developed in these areas, driving economic growth and promoting the conservation of these structures that tend to be excavated for construction materials (Planaguma and Martí 2018).

Volcano (geo)tourism and geoeducation is very poorly developed in Mexico, despite the abundance of young, "aesthetic" volcanoes and the importance of related hazards for inhabited areas (Macias and Arce 2019). As introduced before, the 20 million people living in Mexico City are at risk from large eruptions of several active stratovolcanoes nearby or the birth of a new volcano in the SCVF (Siebe and Macías 2004). The active Popocatépetl volcano may provide an opportunity for tourism and geoeducation yet is located relatively far from the city (2 hrs drive) and the climb on its slopes is prohibited due to significant hazard from frequent explosions. Other stratovolcanoes around the city basin are dormant and not directly threatening but they also stand at high altitude (>4,000 m asl), which make their access also difficult and hazardous. In contrast, the sites herein described are located within the basin and close to important roads and a dense public transportation system, and hence, of easy and safe access to a large number of people, including school groups.

As demonstrated above, the sites expose a wide range of volcanic products in a small area, which may be used to explain a series of important processes that control the eruptive activity and associated hazards and risks. They are particularly relevant in discussing the distinction between monogenetic and polygenetic volcanism, because they contain typical products of both types of activity. In addition, their location at the basin margin and the fact that they contain elevated areas (Kipukas; domes and cones) offer viewpoints ("miradores") that allow to appreciate the range of surrounding volcanic landscape forms and provide impressive views over the city.

The identified sites contain elements of biodiversity, which gives them aesthetic qualities and additional values for environmental education. The identified links between biodiversity and geodiversity is a strong asset to propose a multi-disciplinary approach to nature and the documented range of threats also allow to address anthropogenic impacts to make them visible and discuss possible solutions for the preservation of natural elements.

In summary, the studied sites have several characteristics (elevated values of geological and biological diversity, accessibility, safety, logistics, and population density) that indicate that they have potentially high values for geoeducation and geotourism (Brilha 2016). In the following, we explore the ways these values could be used by the local communities, for their proper benefit.

5.5. Field excursions on geopaths

If well-designed, geotrails are effective means to develop geoeducation and geotourism and allow to raise awareness on geological processes and environmental issues (Stolz and Megerle 2022). To explore the use of such tool at the studied parks and surrounded area and discuss our findings with the local communities, we designed itineraries in each area and organized field excursions addressed to a non-academic audience. In our case, we name them geopaths instead of geotrails because they include streets and do not require hiking equipment. The geopaths are 2 to 3 km long and excursions lasted 2 to 3 hours.

The itineraries include 6 to 9 stops both at well-preserved outcrops of the diverse geological formations present in each area and at viewpoints that allowed to observe and describe the general geological and geographic context. In the case of El Arenal area, the geopath starts at the park, stops at a complete fallout and paleosol sequence, visits a quarry into Cerro Magdalena dacitic dome, and ends on top of the young Yololica scoria cone (Figure 3). In the Viaje a la Naturaleza study area, we designed two geopaths that were implemented separately. In the residential area of Jardines en la Montaña, the geopath starts at the community center, stops at outcrops of Xitle lava units of aa and pahoehoe types, successively, and ends at the Viaje a la Naturaleza park where the Kipuka of the same name outcrops (yellow itinerary on Figure 6). In the Bosque de Tlalpan, the path goes across the Zacayuca Kipuka with good exposures of clay soils covered by a thick white pumice layer, before crossing aa-type Xitle lavas and Viaje a la Naturaleza lava Kipukas (blue itinerary on Figure 6).

The excursions were implemented from May to September 2023. At Viaje a la Naturaleza, the excursion was offered during a local ecological fair ("feria de ecología") organized by the local neighbor association, which was advertised locally but also attracted people from elsewhere in the city. At Bosque de Tlalpan, the excursion was planned with help from the managers of a local market who advertised the event and organized on-line inscriptions for the public in general. At El Arenal, the excursion was planned with the "comisariado de bienes comunales" who called on the team of local people in charge of forest maintenance ("brigada"). There was between 20 and 40 people participating each time.

All these field excursions were highly successful, in the sense that the participants, who had diverse background and socio-economical status, engaged actively in activities of observation of the local geological elements and discussions about interpretations, hence fulfilling our aim to raise interest on the local geology and related processes. Biologist colleagues were actively involved in the excursions, which allowed to highlight the strong relationship between the geodiversity and biodiversity and provide a more comprehensive discourse on nature and related ecosystem services.

According to our observations, the local people, who have few knowledges on geology and biology, were particularly pleased to be able to interact directly with experts in those fields. An important factor that increased the interest of the participants in the excursions is that they took place almost literally "in their back garden", so that they could relate the information directly to their own observations of their surroundings (Stolz and Megerle 2022) and make sense of those. These social aspects are being investigated and results will be presented later-on.

6. Conclusions and perspectives

Prior to this study, the Xitle volcano was the only element considered as a geoheritage feature in the SW corner of the Mexico City basin. Our detailed geological study of two public parks managed by local communities and their immediately surrounding area shows that this area is more diverse than previously thought and displays significant geodiversity due to the overlap of two main volcanic ranges of distinct age, volcano type, and lithologies (Sierra de las Cruces and Sierra Chichinautzin). Due to their geodiversity and high accessibility, the parks here described have high geoeducational potential and geotouristic values, which make them a geoheritage for the local communities. They also present significant biodiversity that is directly related with the geodiversity and create a geo-bio-heritage. We designed geopaths and implemented field excursions which were successful in raising the interest of local residents and park managers about this natural heritage and the threats that need to be addressed in order to achieve its conservation.

To consolidate the close relationship we established with the communities and enable the transmission of knowledge in the long term, we are preparing field guides of the geopaths that combine the geo and bio-information for each stop, and present it in a simple way with pictures and sketches. At El Arenal, we are collaborating in the publication of a book that promotes the natural and cultural values of the village ("pueblo originario"). Those documents, which will be published separately in Spanish, will be valuable for the local communities as they provide necessary elements to consolidate their respective strategies of conservation and promotion of their local park and related geo-bio-heritage.

As a final note, we argue that our project represents the first step of an efficient strategy to promote the geo-bio-heritage to local communities, raise awareness on the associated threats and contribute to improve the communication between scientists and the community. These measures could help to reduce the science-society gap and increase the resilience to volcanic hazards. It is also an example of multi- and transdisciplinary work that provides the necessary scientific and community knowledge to enable the preservation of geo-bioheritage. Research in the future could include a systematic survey of the perception of the local community, park managers and the authorities about their local geoheritage using tools of social mapping. The educational potential of these parks should also be explored further, as they could be used as informal facilities where place-based education can be conducted.

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