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

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1 **Xitle Volcano Geoh heritage, Mexico City: Raising awareness of natural hazards and**  
2 **environmental sustainability in active volcanic areas.**

3

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13

14 **Abstract (250 words)**

15

16 The conservation of geosites in a region can foster its sustainability and develop geotourism.  
17 These geosites provide geoeducation, raise people's awareness on natural hazards and  
18 increase their resilience. Low-income cities located in tectonically active areas combine high  
19 geohazards with high vulnerability and low sustainability. Geosites in these cities should be  
20 a tool to decrease people's vulnerability and foster sustainable development. Mexico City is  
21 an ideal case study for its environmental and social issues and its setting in an active

22 continental volcanic arc. The 1,700 yrs-old Xitle volcano, located in the city's SW corner, is  
23 a small scoria cone that erupted once, feeding an extensive lava field on which >600,000  
24 people now live. The lavas are very well exposed due to thin soils and extensive quarrying.  
25 The Xitle lavas covered the first urban center in the Mexico basin, except for the main  
26 pyramid that has become a major archeological site. The cone and lavas have significant  
27 geodiversity, sustaining a unique and biodiverse ecosystem. The country's largest university  
28 preserves the lavas in an ecological reserve. We describe four exceptional geosites, assess  
29 their values, and discuss their relevance for addressing issues such as nature preservation,  
30 environmental sustainability, social inequalities, and natural hazards. The Xitle volcano  
31 provides a wide range of benefits for the city that are nonetheless unknown to its inhabitants.  
32 We describe ongoing initiatives to disseminate such information, such as the Geopedregal  
33 site, and propose ways that this heritage could be further protected and used by the city in a  
34 sustainable way.

35

#### 36 **Keywords (4-6)**

37 Volcanic geosites, geoeducation, geodiversity, geohazards, sustainability

38

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40

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52

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54 Not applicable

55

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57 Not applicable

58

### 59 **Code availability**

60 Not applicable

61

### 62 **Authors' contribution**

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

67

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78 reviewers provided valuable comments and suggestions that improved the manuscript.

79

80 **Text**

81

82 **1. Introduction**

83

84 The preservation, recuperation and valuing of natural sites in cities is a way to promote nature  
85 conservation, environmental sustainability and human wellbeing (e.g., Hough 2004; Jim  
86 2004; van den Berg et al. 2010). The importance of biological elements for attaining these  
87 benefits is widely recognized, yet geological elements (such as rocks, landforms, fossils, etc.)  
88 are generally not or hardly considered in environmental policies and urban planning (e.g.,  
89 Boothroyd and McHenry 2019; Gray 2013; Brilha et al. 2018; Gray 2018; Gordon et al.  
90 2018). Accordingly, protected green spaces are relatively common in cities (e.g., Jim 2013;

91 Zambrano et al. 2019), whereas analogous places for rocks and landforms are rare (Portal  
92 and Kerguillec 2018). Construction works continuously expose new outcrops, but these are  
93 generally viewed as unaesthetic and a source of danger through falling blocks, hence,  
94 exposures are frequently destroyed or covered, losing their potential value (Reynard et al.  
95 2017; Vereb et al. 2020). In the long term, the original topography and landscape is altered  
96 significantly, alienating people from their local geology, territory and natural setting (e.g.,  
97 Reynard et al. 2017; Ticar et al. 2017; Clivaz and Reynard 2018), with potentially disastrous  
98 consequences for their environmental wellbeing and their awareness of natural hazards.

99         Geoparks are good examples of how the conservation of remarkable geological  
100 elements of a territory (i.e. geoh heritage) can be used through education and tourism to  
101 promote sustainability (e.g., McKeever and Zouros 2005). These programmes are based on  
102 the identification of sites that contain geological elements either with high scientific value  
103 (geosites) or with limited scientific value but high touristic and educational potential  
104 (geodiversity sites) (Brilha 2016). The conservation and valuing of geosites in cities could  
105 help them reach greater environmental sustainability, increase human wellness, as well as  
106 develop new sources of revenue through geotourism (Rodrigues et al. 2011; Gorska-  
107 Zabielska and Zabielski 2017; Ticar et al. 2017; Reynard et al. 2017). Urban geosites can  
108 also enhance knowledge and people's perception of the relationship between urban  
109 development, culture, and natural processes (Del Monte et al. 2013; Picar et al. 2016, 2017;  
110 Reynard et al. 2017). Such initiatives are particularly relevant in areas with high georisks,  
111 because they provide geoeducation and strengthen local communities, improving social  
112 awareness and resilience to hazards and reducing disaster risk (Eiser et al. 2012; Fassoulas  
113 et al. 2018; Pavlova 2019; Petrosino et al. 2019). Identifying geosites in cities of developing

114 countries that are located in tectonically-active areas (i.e. close to tectonic plate edges) is  
115 crucial because these cities combine multiple geohazards (such as earthquakes, volcanoes,  
116 landslides, flooding) with high vulnerability and low sustainability due to a wide range of  
117 socio-economic, educational, and political issues (e.g. Hardoy et al. 2013). The metropolis  
118 of Mexico City is one of the largest urban areas in the world (>20.9 million inhabitants, Censo  
119 de Poblacion y Vivienda 2010, INEGI), with infamous environmental problems (e.g.,  
120 Schteingart 1989). Because of its location in a lake basin at the center of an active volcanic  
121 arc, the city is exposed to numerous natural hazards including earthquakes, volcanic  
122 eruptions, water shortages, subsidence, landslides and flooding (e.g. Siebe and Macias 2006;  
123 Aragón-Durand 2007; Mancebo 2007; Ortiz-Zamora and Ortega-Guerrero 2010). Although  
124 these hazards affect the society as a whole, poor people living in the city's outskirts are  
125 particularly vulnerable (e.g., Mancebo 2007; Eakin et al. 2016).

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

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

159



160       **2. The Xitle volcano**

161

162 Xitle volcano consists of a small scoria cone (140 m high, 500 m wide) and a large lava field  
163 (ca. 80 km<sup>2</sup>) that were produced by a single basaltic eruption less than 1670 yrs ago (Delgado  
164 et al. 1998; Siebe 2000). The volcano erupted at 3000 m asl, on the northern flank of the  
165 Sierra Chichinautzin mountain range that borders the south of Mexico Basin (Fig. 1). After  
166 an initial explosive phase, the volcano effused lavas that flowed down into, and invaded the  
167 southwest part of the Mexico basin, burying most of a pre-hispanic city (Cuicuilco) and  
168 reaching the shores of the ancient, now mostly drained, Xochimilco and Texcoco lakes at ca.  
169 2250 m asl, 12 km from source. The lava field is complex and consists of multiple units  
170 indicating a pulsing effusive activity punctuated by minor explosive phases. The large  
171 volume erupted (>1 km<sup>3</sup>) suggests that the eruption lasted a decade or more. The lavas form  
172 barren, rocky land with irregular topography that was mostly left un-populated, until the  
173 central campus of the National University of Mexico (UNAM) was built in 1948-1952 on the  
174 far end of the flow (Fig. 2A, 2B; Carrillo-Trueba 1995; Salas Portugal 2006). At about the  
175 same time, the “Jardines del Pedregal” (gardens of the rocky place), an exclusive residential  
176 area just west of UNAM, was constructed under the guidance of world-renown architects and  
177 artists (e.g., Rivera 1945; Pérez-Méndez 2007). The urbanization of the lava continued  
178 southwards and towards the volcano, with the construction of housing and infrastructure for  
179 the Olympic games of 1968 (Fig. 2C), followed by extensive residential areas and  
180 commercial centers in the early 1970s (Fig. 2D). By now, the city has incorporated almost  
181 the entire lava field, except for a few patches, which are under high stress (Cano-Santana et  
182 al. 2006). The largest and best conserved of these patches is the “Reserva Ecological de San

183 Angel” or REPSA, an ecological reserve with a core zone of 171 ha and a buffer zone of 66  
184 ha that was created in 1983 inside UNAM (<http://www.repsa.unam.mx>; Zambrano et al.  
185 2016). About 660,000 people currently live on the lava field (Hernández-Robles 2019), most  
186 of them without knowing that they sleep on a bed of lava.

187

188

### 189 **3. Characterization of the Xitle volcano area: Geological, environmental and** 190 **additional values**

191

#### 192 **3.1 Geological processes and volcanology**

193 Xitle volcano is located in an area of intense and highly active volcanic, tectonic and  
194 sedimentary processes (Fig. 1). It is part of the Quaternary Sierra Chichinautzin volcanic  
195 field, which consists of more than 200 small volcanic edifices, most of them scoria cones and  
196 lavas (e.g., Bloomfield 1975; Martín del Pozzo 1982; Márquez et al. 1999; Siebe 2000; Arce  
197 et al. 2013). This volcanic field forms the central part of the active Trans-Mexican volcanic  
198 belt, a wide band that crosses Mexico east-west and includes stratovolcanoes, vast fields of  
199 small, monogenetic volcanoes, and some calderas (Fig. 1). The axial part of the belt is  
200 affected by extensional forces that created a series of high-altitude (> 2000 m asl) tectonic  
201 basins, including the Mexico basin where the city is located (Fig. 1). The basins are filled by  
202 lacustrine and volcanoclastic sediments and were occupied by shallow endorheic lakes that  
203 have largely disappeared due to anthropogenic activity. The Xitle volcano is a strong marker  
204 of this highly dynamic setting, as its cone was built on the border of the graben and its lava  
205 interacted with one of the pre-existing lakes in the basin.

206 In terms of volcanology, Xitle is a fine example of a basaltic scoria cone and  
207 associated lavas, which are the most common volcanic structures on Earth (Fig. 3C; Wood  
208 1980). This type of volcano is commonly called monogenetic, as they are formed by single  
209 (mono) eruptions with one cause (genetic). While scoria cones are abundant along the Trans-  
210 Mexican volcanic belt, basalts are atypical in subduction settings, and especially so the  
211 alkaline, Ocean Island Basalt-type erupted at Xitle. This drives strong interest on this  
212 particular volcano for geochemical studies on the source of magmatism in this region (e.g.  
213 Straub et al. 2008).

214 Both the surface and the interior of Xitle lavas are exceptionally well exposed,  
215 because soils are barely formed, due to the young age of the basaltic lava that is hard to erode  
216 in the arid climate, and because of abundant quarrying due to the expansion of Mexico City.  
217 Excavations have taken different forms with time. Large quarries made to extract building  
218 stones were most prominent prior to the urbanization of the area. Important road cuts were  
219 made when large avenues (Insurgentes sur, Periferico sur) were constructed, and now  
220 excavation is restricted to small private areas, with the aim to construct underground parking  
221 areas and to anchor structures against earthquakes. Most of these excavations and any  
222 resulting exposures of the internal structure of the lava are however covered up when the  
223 work ends, which reduces the number of long-lasting exposures that can be of use for  
224 research or education. Early-on, the outcrops resulting from the active quarrying have  
225 motivated the pioneering works of Waitz and Wittich (1910), Wittich (1919), Schmitter  
226 (1953), and Badilla-Cruz (1977), and the more recent works of George Walker, the father of  
227 modern volcanology, who revisited the early interpretations (Walker 1993, 2009). The many  
228 sections cut through the lavas have also permitted numerous studies on the internal magnetic

229 properties of basaltic lava flows (e.g., Cañon-Tapia et al. 1995, 1996). The quarrying is an  
230 example how geoheritage can be promoted by extraction, *if* the exposures are accessible and  
231 preserved.

232

### 233 **3.2 Volcanic and seismic hazards**

234 Due to its tectonic setting, Mexico City is surrounded by many young, active volcanoes and  
235 hence exposed to significant volcanic hazards (Fig. 1, Siebe and Macías 2006). The most  
236 obvious source of hazards is the Popocatepetl stratovolcano, which has been in eruption since  
237 1994 and the ash of which occasionally reaches the city. However, the dormant Nevado de  
238 Toluca volcano located 50 km west of the city and not visible from it (Fig. 1) has deposited  
239 thick pumice layers in the Mexico basin, and is hence also a potential hazard that is unknown  
240 to city dwellers. Another potential, yet unknown hazard is that of the formation of a new  
241 monogenetic volcano within the Sierra Chichinautzin volcanic field. This is also a probable  
242 impact even on Mexico City, as 14 such volcanoes (including Xitle) have erupted during the  
243 last 15,000 yrs (Fig. 1, Siebe et al. 2004; 2005; Arce et al. 2015; Guilbaud et al. 2015). These  
244 volcanoes are poorly known by the public, despite the famous eruption of the Paricutin  
245 volcano in Michoacán in 1943-1952 (Luhr and Simkin 1993), being a classic Mexican  
246 example. Xitle volcano is the most recent example of such type of volcano near the city, its  
247 products are well-exposed, and there is clear evidence for its direct impact on human  
248 settlement (see below). Hence, it is key to study and educate about hazards linked to  
249 monogenetic eruptions in this area.

250 About seismic hazards, during the past centuries, Mexico City has been affected by large  
251 magnitude earthquakes that have caused serious material damage and loss of life (e.g.

252 Campillo et al. 1989; Singh et al. 2018). During those, the uneven distribution of the damage  
253 revealed the crucial role of the ground firmness, the so-called site effect, on the intensity and  
254 magnitude of the ground shaking. This then resulted in the zoning of the Mexico basin in  
255 terms of seismic hazards and associated construction rules (e.g., Campillo et al. 1989; Flores-  
256 Estrella et al. 2007). By being firm and located on the edge of the basin, Xitle lavas are a safe  
257 area to live and work, and thus a testimony of the natural factors affecting seismic hazards.  
258 It is noteworthy that the UNAM campus in the city hosts the Servicio Sismológico Nacional  
259 (SSN) that is in charge of surveying the seismic activity in the whole country and informing  
260 authorities and population ([www.ssn.unam.mx](http://www.ssn.unam.mx)). It is hence a key actor for the mitigation of  
261 seismic risks.

262

### 263 **3.3 Hydrogeology, water resources, and flood hazards**

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

274

### 275 **3.4 Biodiversity, ecology and environment**

276 Young basaltic lavas are a very peculiar substrate on which plant colonization is slow and  
277 selective, hence fostering the formation of a specific ecosystem (e.g., Del Moral and Grishin  
278 1999). The vegetation of the Xitle lava field has been mapped by Carrillo-Trueba (1995),  
279 revealing a diverse plant pattern that varies mostly with altitude. While high-standing areas  
280 (>2,500 m asl) are dominated by forests of pine tree, oak and fir (e.g., the vent area, Fig. 3C),  
281 low-altitude areas (<2500 m asl) are mainly covered by a xeric scrub dominated by  
282 *Pitocaulum praecox* that is native to Central Mexico (Rzedowski 1954) (e.g., the distal lavas,  
283 Fig. 3D). The *Pitocaulum praecox* is a peculiar bush locally named “palo loco” or 'mad  
284 branch', in Spanish, because it flowers in the dry season when the rest of the vegetation is  
285 almost completely dry. This vegetation type is associated with a high biodiversity, having  
286 almost 1,820 species of all taxonomic groups recognized, 32 of which are under protection  
287 by Mexican laws and 54 of which are endemic to Mexico (e.g., Lot and Cano-Santana 2009;  
288 Zambrano et al. 2016). The specifics of this ecosystem strongly rely on the peculiar  
289 microtopography of the lava, which yields variable conditions of temperature, humidity,  
290 light, and organic soil depth, promoting many biological adaptations in a climate alternating  
291 between clear dry and rainy seasons (e.g., Castellanos-Vargas et al. 2017).

292

### 293 **3.5 Archaeology and radiometric dating**

294 Xitle has a profound significance for archaeology, as its eruption destroyed the first large  
295 urban center of the Mexico basin (Cuicuilco). The abandonment of this site as a possible  
296 consequence of the eruption coincides with the expansion of the city of Teotihuacan, located  
297 further north, that became one of the largest urban areas in the world in the Classic period,

298 AD 350-650 (e.g. Cummings 1926; González et al. 2000; Siebe 2000). Although it is yet to  
299 be validated, as there are no historical accounts and radiometric dates for the eruption are  
300 variable (see discussion in Siebe 2000), the eruption is pictured as responsible for a major  
301 human disaster, as portrayed in paintings located in a small museum in the Cuicuilco  
302 archaeological site and on the town hall of Tlalpan, a district of Mexico City that was  
303 originally a village at the edge of the city (Fig. 3A).

304         Due to its archaeological significance and excellent exposure, the Xitle lava is the  
305 most dated in Mexico, both by radiocarbon and paleomagnetic methods (e.g., Siebe 2000;  
306 Urrutia-Fucugauchi et al. 2016). The first radiocarbon age that was acquired for this eruption  
307 ( $2,422 \pm 250$  yrs BP) was one of the first ages obtained by the radiocarbon method worldwide  
308 (Arnold and Libby 1951), which shows its importance for the development of a key dating  
309 method for the Holocene and Late Pleistocene. Series of holes drilled in nearly every major  
310 vertical section in the lavas reflect also its extensive use for the paleomagnetism calibration  
311 that has a wide range of applications worldwide (Fig. 3B).

312

### 313 **3.6 Arts and aesthetics, architecture and cultural heritage**

314 The Xitle lava has been the source of abundant creative work, which expresses its  
315 significance for the cultural identity of this area and makes it part of the intangible heritage.  
316 The peculiar landscape formed by the lavas (locally called “Pedregal de San Angel”) has  
317 inspired many artists in the past, including painters like Diego Rivera, David Alfaro  
318 Siqueiros, Gerardo Murillo (“Dr Atl”) and Joaquin Clausell, photographers (Hugo Brehme  
319 and Armando Salas Portugal), sculptors (Federico Silva, Helena Escobedo, Mathias Goeritz,  
320 Francisco Soto), poets (e.g. Carlos Pellicer) and architects (Luis Baragan, Max Cetto house

321 studio). It remains an inspiration for artists today such as Abraham Cruzvillegas, with his  
322 provocative wall of trash named “Reconstrucción” (2016), illustrators like Aslam Narvaez  
323 and Elvia Esparza, and many photographers who recognize the unique beauty of both the  
324 lava forms and biodiversity. Several monuments of the “Ruta de la amistad” (route of  
325 friendship), a series of 20 sculptures made by renowned artists in the southern part of Mexico  
326 City for the 1968 Olympic games, were strongly inspired by the lava outcrops on which they  
327 were built, and some of the artistic works remain placed where the lavas are nicely exposed  
328 (Camarena-Berruecos 2010). The natural ecosystem formed over the lava and preserved in  
329 the ecological reserve makes UNAM’s main campus to be mentioned as the most beautiful  
330 university in Latin America, and has been described as “a green oasis in the middle of a  
331 megalopolis” (Krieger 2008).

332 As for architecture and cultural heritage, the Xitle lava has been used abundantly as building  
333 stone for its aesthetic value, resistance to erosion and direct availability at construction sites.  
334 The rocks hence form part of the architectural heritage of the area and contribute to its identity  
335 inside the immense, multi-cultural megalopolis. In planning the exclusive “Jardines del  
336 Pedregal” residential area that was constructed over the Xitle lava, Diego Rivera, probably  
337 Mexico’s best known and most emblematic artist along with his wife Frida Kahlo,  
338 highlighted the benefits of the use of locally derived lava blocks that are valuable for their  
339 homogeneity, solidity, low cost, and beauty (Rivera 1945). The Anahuacalli museum that he  
340 built still hosts his collection of prehispanic objects and is a clear demonstration of these  
341 precepts (Fig. 3E). These same ideas directed the planning of the central part of the UNAM  
342 campus, which is considered as one of the most important architectural works of the last  
343 century, and which was declared World Heritage site in 2006 (Technical report for UNESCO



344 by the Coordinación de Proyectos Especiales, UNAM 2005). Another example is the house  
345 called “casa del Indio” in the Coyoacán district that was built mostly by lava, by a famous  
346 architect, Manuel Parra, for an emblematic Mexican actor (Emilio Fernandez) and that can  
347 be visited. Besides these sites, the distinct light to dark grey microvesiculated Xitle stone is  
348 part of many buildings, walls, stairs, and platforms in the SW corner of Mexico City, which  
349 highly contributes to the aesthetics and sense of identity of this area of the city. Nevertheless,  
350 its use is declining, and efforts should be made to promote it in the construction of new  
351 buildings, in order to conserve the area’s identity.

352

353

#### 354 **4. Description of the geosites**

355

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

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

372

#### 373 **4.1 Xitle vent geosite**

374 This site is located at high altitude, on the northern flank of the Sierra Chichinautzin range  
375 (Figs. 1, 4). We first provide a short summary, and then describe the area in details, presenting  
376 maps of the volcanological elements (Fig. 5A, B) and the related vegetation pattern (Fig. 5C),  
377 and showing photographs of the main elements (Fig. 6). As developed below, this site has  
378 high geodiversity which is strongly and clearly linked with elements of pedodiversity and  
379 biodiversity, of significant scientific and educational interest.

380

381 **Summary:** This site contains typical, proximal products of Strombolian-style basaltic  
382 activity (the weakest form of explosive volcanic activity) that are particularly well preserved  
383 and exposed. The area also features a range in vegetation cover and dominant tree species  
384 that are correlated with variations in the parental material (lava, scoria or tephra) and the  
385 overlying developed soil, the orientation of the cones' slopes (slope aspect) that controls the  
386 amount of solar insolation and humidity, and with the variation in altitude that allows  
387 different rainfall and humidity regimes. The dominant tree species are either endemic to  
388 Mexico or to Central Mexico, which is of biological relevance because of their associations  
389 and also have importance for their educational value. The position of the main cone on an  
390 elevated plateau directly south of the city provides panoramic views of the Mexico basin and

391 surrounding volcanoes that are both aesthetic and instructive. As for touristic values, this site  
392 is a pleasant, green area with low atmospheric contamination that is easily accessible by city  
393 dwellers. Numerous people go to this area in the weekends to enjoy small restaurants and  
394 outdoor activities such as horse riding, hiking, and mountain biking. The walking paths are  
395 easy and do not require specific equipment. For the cultural aspect, we have witnessed locals  
396 engaged in religious ceremonies that take place near the main crater, but this aspect needs to  
397 be investigated further in the future. Scientific values are described in more detail below,  
398 distinguishing between volcanological, biological and pedological aspects.

399

400 **Scientific interests. Volcanology:** The vent area consists of a scoria cone (Xitle proper) and  
401 a spatter and lava cone (Xicontle) that are aligned in a broad east-west direction, suggesting  
402 a fissure (Fig. 5A, B). This type of 'monogenetic' volcano is the most abundant on the planet,  
403 and its components are particularly well-preserved and well-exposed here. The alignment of  
404 the Xitle and Xicontle vents highlights the ascent of the magma driving the eruption along  
405 tectonic planes in the crust (faults), forming dikes that create a line of eruptive vents when  
406 intersecting the surface. The scoria cone has a deep internal crater (50 m) and relatively steep  
407 (ca. 30°) smooth outer slopes (Fig. 5B), which probably explain the name of Xitle that means  
408 belly button in the indigenous Nahuatl language. This morphology reflects the young age of  
409 the cone whose original aspects have not been significantly affected by weathering. Small  
410 paths allow the ascent of Xicontle and Xitle and follow their crater rim (Fig. 6A) and at Xitle,  
411 descend to the bottom of the crater (Fig. 6B). The slopes of the scoria cone's crater have  
412 gullies and small-scale landslides made of loose, bomb-size scoria, indicative of erosion by  
413 colluvial transport that controls the morphological evolution of the crater (Fig. 6B).  
414 Viewpoints offer clear views of the crater interiors, the southern part of the Mexico Basin

415 (commonly covered by smog), and Ajusco's northern slopes, that are important components  
416 of the general geological and geographical setting (Fig. 6C). On clear days, the Popocatepetl  
417 and Iztaccihuatl stratovolcanoes that border the Mexico Basin to the east can be seen. Cuts  
418 along the paths and gullies on the slopes expose the scoria cone interior that consists of an  
419 alternation of scoria and ash layers (Fig. 6D), as well as lava bombs and short flows. Such  
420 deposits are typical products of mildly-explosive activity that occurs at basaltic cones. In  
421 contrast, Xicontle is made of a superposition of spatter layers and thin (<1 m) lavas exposed  
422 in the crater, which are the products of lava fountaining that typically occur during weak  
423 explosive activity along fissures. The good exposure of these products of weak to mildly-  
424 explosive basaltic volcanism represents an educational asset. Of additional interest in this  
425 area, is a lava flow unit to the east of the main cone that has no tephra cover, indicating that  
426 it formed late, after the cone-forming explosions (Fig. 5A). These lavas host a system of  
427 caves (lava tubes) linked to collapse structures (skylights), and some channels. The lava tubes  
428 are important elements of basaltic lavas that strongly contribute to the large areas covered by  
429 these flows, due to being very well insulated (Keszthelyi 1995). They are exposed as empty,  
430 elongated cavities when their interior is drained, which probably occurred here at the end of  
431 the eruption. These interesting aspects of the volcano are worth further investigation given  
432 their relevance for understanding the recent, impactful volcanic activity close to Mexico City.  
433

434 **Pedology:** There are interesting links between the elements of geodiversity of the vent area,  
435 and other factors controlling the soil formation (relief, microclimate and organisms).  
436 Variations in the topography in the vent area create some diversity in the soils. On the cone,  
437 soils are formed from recently deposited unconsolidated volcanic ash and are hence shallow,  
438 very stony, with incipient accumulation of organic matter and very weak structure,

439 classifying as haplic Regosol, tephric, skeletal (humic) (Fig. 6H, Table 2, WRB IUSS  
440 Working Group 2015). They are also highly porous and allow root growth to depths of up to  
441 70 cm. Soil depth and color vary with altitude, slope angle, and slope orientation. Soils are  
442 deeper at higher altitude because of an increase in the amount and size of the deposited  
443 unconsolidated tephra material. Steeper slopes have lower material stability, lower  
444 accumulation and hence less soil depth. Slope orientated to the north causes shady, less  
445 exposed areas to be more humid and have more trees and hence be more organic (darker  
446 colored soils). In contrast, slopes with southern, sun exposure are drier and have light-colored  
447 soils (Porta et al. 2019). Hence, the south-facing hillside inside the crater with a 35° slope,  
448 has low material accumulation, greater sun exposure, less humidity and a vegetation of grass  
449 and few trees. The result is a shallow, light-colored soil, because of low organic matter  
450 accumulation.

451

452 **Biology:** The vegetation in the vent area follows a pattern that matches the distribution of the  
453 volcanological elements (cone, crater, lava), each of them presenting distinct soil types and  
454 microenvironments due to variations in altitude and sun exposure (Fig. 5C). Our field  
455 observations in February 2020 are generally consistent with the map of Carrillo-Trueba  
456 (1995) although we noted some differences. The outer-slopes of the main cone that were  
457 mapped as an alder forest by Carrillo-Trueba (1995), present a wide diversity of trees that  
458 includes, in addition to alder (*Alnus firmifolia*, Fig. 6E), birch (*Betula pubescens*, Fig. 6E),  
459 pine trees (*Pinus teocote*), widespread strawberry trees or madroño (*Arbutus xalapensis*, Fig.  
460 6B, C, F), oaks (*Quercus* spp.) and yuccas (*Yucca filifera*, Fig. 6B). Vegetation inside the  
461 crater is distinct from that on the outer-slopes and varies with the slope orientation. The north-  
462 facing, slopes are covered by a fir forest (*Abies religiosa*, locally named abeto or oyamel,

463 Fig. 6B) whereas the south-facing slopes are dominated by grass and small shrubs  
464 (*Muhlenbergia macroura*, *Arctostaphylos pungens* and *Festuca tolucensis*). Vegetation on  
465 the lavas depends mostly on the tephra cover (Fig. 6C). Tephra-free lavas (late lavas) are not  
466 cultivated and have just a few pine trees (*Pinus hartwegii*). In contrast, lavas that are covered  
467 by tephra (early lavas) have a mature forest of *Pinus teocote* regenerated with *Pinus*  
468 *leiophylla* (Fig. 6G), in addition to strawberry trees (*Arbutus xalapensis*), succulents (*Sedum*  
469 *oxypetalum*) and grass. An area south of the cone that was not covered by Xitle lavas features  
470 cultivated fields (Fig. 6C). Associated and conspicuous native vegetation in the area include  
471 thistle (*Cirsium ehrenbergii*), tepozán (*Buddleja cordata*), boneset (*Ageratina glabrata*) and  
472 maguey (*Agave salmiana*, Fig. 6A). All these plants are important hosts for pollinators such  
473 as bats, nocturnal butterflies, hummingbirds, bees, wasps and beetles. Furthermore, the  
474 different plant species live in symbiosis with different types of mycorrhizal fungi that are  
475 extremely important for biogeochemical cycles and to maintain healthy soils, fulfilling many  
476 ecological functions such as carbon sequestration, nutrient translocation, soil stabilization  
477 and infiltration facilitator (Table 1).

478

#### 479 **Other sites with similar scientific value**

480 Other cones of the Sierra Chichinautzin present similar characteristics, although the cone and  
481 lava morphology, vegetation pattern, and soil cover vary widely with the volcano's age and  
482 location (altitude, precipitation) giving a chronosequence of volcanic deposits and soils  
483 (Peña-Ramírez et al. 2009). Cones that present particular interest for geosite development  
484 due to their easy access and good level of knowledge are Teuhtli (Siebe et al. 2005; Guilbaud

485 et al. 2015), Pelado (Lorenzo-Merino et al. 2018), Dos Cerros (Agustín-Flores et al. 2011;  
486 López-Valdés 2019) and Chichinautzin (Peña-Ramírez et al. 2009; Reverchon et al. 2010).

487

## 488 **4.2 Cuicuilco geosite**

489

490 **Summary:** This site encloses an archeological and ecological park that is located at the  
491 crossing of two main avenues in southwest Mexico City and several large shopping centers  
492 (Loreto-Pena Pobre or Cuicuilco, Periferico Sur), and hence represents a natural green island  
493 in a dense urban area with heavy traffic and a constant flow of people (Figs. 3D, 7A). The  
494 park has a round pyramid that was surrounded and partly covered by Xitle lavas (Fig. 7A),  
495 which superbly and very clearly illustrates the great impact of a relative minor eruption on a  
496 major urban area at the beginning of our era (González et al. 2000; Hubp et al. 2001). This  
497 place is also strategic for inferring the pre-existing topography, climate and human  
498 occupation, as well as the eruption chronology, through the study of the lava forms and the  
499 deposits preserved below (paleosols, embedded artefacts, ash) (Figs. 7B-D; Solleiro-  
500 Rebolledo et al. 2016). In addition, it includes a patch of the lava field with typical landforms  
501 and associated flora and fauna, that can be observed along pleasant walking paths (Fig. 7E).  
502 The top platform of the pyramid provides clear views over the southwest corner of the  
503 Mexico basin and the northern slopes of the Sierra Chichinautzin, featuring specifically the  
504 Xitle cone and Ajusco stratovolcano. On clear days (a rare occurrence), the Teuthli cone and  
505 the Popocatepetl stratovolcano can be seen to the southeast. Of cultural and artistic  
506 significance, the recently-restored sculptures and monuments of the “Ruta de la Amistad”  
507 (friendship route) built directly on the lava can be observed on a nearby roundabout

508 (Camarena-Berruecos 2010). Onsite, there is a small museum that presents basic information  
509 about the setting and archaeological findings. There is also a painting representing the  
510 destruction of the pyramid by the Xitle eruption.

511

512 **Archaeological interest:** The rounded pyramid is one of the few existing in Mexico and is,  
513 with the exception of small mounds nearby, the only remaining building of Cuicuilco City  
514 (Cummings 1926). Cuicuilco (700 BP-150 AD) is considered the first major urban center in  
515 the Mexico Basin (Heizer and Bennyhoff 1958), with a peak occupation of >20,000  
516 inhabitants (Sanders et al. 1979; Parsons 1989). Its great economic and political power is  
517 reflected by a majestic complex of buildings surrounding a temple with a conical truncated  
518 base, about 110 m in diameter and 20 m in height (Kelly 1982). There is still considerable  
519 debate over whether the eruption directly caused the abandonment of Cuicuilco and the  
520 migration of its population to Teotihuacan or if both events are not connected. If it did, then  
521 the eruption caused a major natural disaster (e.g, Heizer and Bennyhoff 1958, 1972; Córdova  
522 et al. 1994; Siebe 2000; Urrutia-Fucugauchi et al. 2016).

523

524 **Scientific interests. Stratigraphy and paleoenvironment:** The archaeological excavations  
525 created numerous cuts through the lava that reveal the vesicular interior of the flows and,  
526 more peculiarly, the surface below. A tunnel excavated below the lava exposes from top to  
527 bottom: the billowy base of the lava that is proof of its emplacement as inflating pahoehoe  
528 lobes, a thin reworked dark ash layer produced by early explosive activity at the cone, and a  
529 buried soil (paleosol) that is locally indurated and transformed into red brick due to the lava  
530 heat (Fig. 7B, Solleiro-Rebolledo et al. 2016). Such a succession very clearly shows the



531 chronology of events that occurred at this important site, being hence of scientific and  
532 educational value. This paleosol preserves important information on the paleoclimate and  
533 human occupation at the time of the eruption (Solleiro-Rebolledo et al. 2016). The ash below  
534 the lava is locally finely stratified, indicative of an intense activity with rapidly-succeeding  
535 strong explosions, and the basal layer contains bits of charcoal which were likely produced  
536 by the burning of vegetation along the advancing lava flow front (Fig. 7C, Siebe 2000). South  
537 of the archaeological park, a cut along a carpark in a commercial center exposes rounded,  
538 pillow-like lava forms that suggest the existence of shallow water in that area at the time of  
539 the eruption (Fig. 7D; Plaza Cuicuilco in Palacio and Guilbaud 2015). This confirms other  
540 inferences that the pre-Hispanic city was located in a deltaic plain, at the convergence of river  
541 streams that flowed down the slopes of Ajusco (e.g., Córdova et al. 1994). Exposed recent  
542 pillow lavas are a rare feature, giving particularly high importance to this site.

543

#### 544 **Other sites with similar scientific value**

545 The contact of the lava with the underlying ground, with a thin ash layer and locally-burnt  
546 paleosol with archeological artifacts, can also be seen in several sites in UNAM, indicative  
547 of the large area occupied by settlements that were affected by early ash from Xitle (Entrada  
548 Principal and Campo de Beisbol in Palacio and Guilbaud 2015). Graves and diverse types of  
549 objects were found in the paleosol in the Copilco quarry located north of UNAM (Gamio  
550 1920). However, this important site that was public from the 1920s to the early 1980s  
551 (Solleiro-Rebolledo et al. 2016), is now only accessible after specific request, from the  
552 offices of the National Institute of Anthropology of Mexico.

553

### 554 **4.3 The Geopedregal geosite**

555

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

575

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

591

592 **Pedology:** The age of the emplaced lava is less than 1700 years and therefore soils are very  
593 shallow (<4 cm) and located only in small morphological depressions, allowing almost a  
594 continuous rock surface. They contain less than 20% of fine particles and low amounts of  
595 nutrients as cations (Ca, Mg, K and Na) but high organic matter, classifying as nudilithic  
596 Leptosol hyperskeletal distric soils (Fig. 8F, Table 2, Siebe et al. 2016). From the point of  
597 view of soil quality, one could say that site quality is poor: soil texture is coarse, causing  
598 excessive drainage and low water holding capacity, nitrogen retention is limited because the

599 organic horizon is thin, but the main function of these soils is infiltration and aquifer recharge.  
600 The diversity in lava morphology in terms of slope, roughness, and fracture pattern, and  
601 associated soil thickness, produces high biodiversity through the crucial role of microsites  
602 (or microhabitats) (Cano-Santana et al. 2006; Castellanos-Vargas et al. 2017).

603 The lavas around the Geopedregal have been covered with anthropic materials introduced in  
604 the early 1970's to build the green landscaped areas of the university covered with lawn,  
605 where technosols are developed that are now at least 1.5 m thick (Fig. 8G). These two  
606 contrasting types of soil (natural vs antropogenic) allow us to explain the ecosystem services  
607 provided by the natural lava soils.

608 **Biodiversity:** Depending on the microhabitats with differential temperature, humidity and  
609 light conditions diverse plant species and community consortia can develop. These range  
610 from cryptobiotic saxicola crust (crust made by organism growing directly on the rock) made  
611 by an association of cyanobacteria, lichens, and bryophytes, to scrub vegetation dominated  
612 by the “palo loco”, agaves and several terrestrial orchids. Some trees species (“Tepozán”:  
613 *Buddleja cordata*, Fig. 8E, “Encino”: *Quercus rugosa*, “Copal”: *Bursera fagaroides* and  
614 *Bursera cuneata*) grow in skylights and deep inflation clefts. “Orejas de burro” (Crassulasean  
615 *Echeveria gibbiflora*) typically grows in fractures and shallow inflation clefts as well as  
616 cactus (“nopal”: *Opuntia tomentosa*, *Mammillaria magnimamma* and the endemic  
617 *Mammillaria haageana san-angelensis*), and the bat-pollinated agave *Manfreda*  
618 *brachystachya* grows on flat surfaces exposed to abundant sunlight. The irregularity for the  
619 surface and the presence of caves also promotes significant diversity in fauna, such as local  
620 mammals and insects (marsupial “Tlacuache” *Didelphis virginiana*, ringtail “Cacomixtle”

621 *Bassariscus astutus*, rodent “Ratón piñonero” *Peromyscus gratus gratus*, and the endangered  
622 bat *Leptonycteris curasoae*).

### 623 **Other sites with similar scientific value**

624 Some sites in the reserve buffer zone also allow visitors to observe the peculiar lava  
625 morphology and partly restored ecosystem (Jardín Botánico, Senda Ecológica and Espacio  
626 Escultórico, in Palacio and Guilbaud 2015). In some places in the UNAM campus and  
627 around, the lava surface is periodically cleared of invading grass (mostly for aesthetic  
628 purposes), conveniently exposing the lava’s microstructures and textures. Outside of UNAM,  
629 the lava and vegetation are partly preserved in localized parches in the Cuicuilco site (Fig.  
630 3D), the “Bosque de Tlalpan” (ID8 in Palacio and Guilbaud 2015), the Huayamilpas park in  
631 Santo Domingo, “Los Encinos” area near the Colegio de Mexico, the main avenue of the  
632 “Jardines del Pedregal” residential area, and the Anahuacalli museum (location of sites on  
633 Fig. 4; Cano-Santana et al. 2006; Camarena-Berruecos 2010).

634

### 635 **4.4 The Pumas Quarry geosite**

636

637 **Summary:** The “Cantera Oriente” (eastern quarry in Spanish) is located at the eastern border  
638 of the UNAM campus (Fig. 9A). Despite its location near to one of the busiest metro stations  
639 of the capital (Universidad station), this place is very quiet green area that was restored with  
640 exotic plant species and contains a lake. This site is known informally as the “Cantera de los  
641 Pumas” because it encloses the training grounds of the infamous “Pumas” UNAM football  
642 team, and visits are allowed only by appointment. The 7.5 ha area belongs to UNAM but was  
643 exploited by the city from 1970 to 1994 (Lot 2007). The remaining artificial cuts of the quarry

644 walls display spectacular exposures across an up to 40 m-thick pile of inflated pahoehoe  
645 flows (sheet lobes and tumuli). These are continuous over a lateral distance of 900 meters  
646 and consists of five main vertical units (Figs. 9B, C; ID2 in Palacio and Guilbaud 2015). The  
647 high total thickness of the lava and its complex internal structure points to years of slowly  
648 advancing lobes, progressively filling a large depression (Guilbaud and Siebe 2009). Water  
649 springs emerge from fractured areas near the base of the lava pile (Fig. 9D) and feed a pond  
650 or small lake that covers 12,000 m<sup>2</sup> (Fig. 9E), demonstrating the role of the lava as an aquifer.  
651 This small lake is surrounded by a green area managed by the reserve that has some interest  
652 in biology and ecology (Lot 2007) as for example the conservation of the endemic Mexican  
653 salamander *Ambistoma mexicanum*.

654 **Scientific interests. Volcanology and paleomagnetism:** The “Cantera Oriente” is the  
655 largest remaining quarry in the Xitle lava which has not been urbanized and where the lava  
656 can still be easily seen and accessed for sampling, which is of considerable interest for  
657 scientific studies. As introduced in section 3, the Xitle lava is probably the most excavated  
658 young basaltic lava in the world, due to the growth of one of the largest cities in the world,  
659 first near its margins and then directly on it. Excavated respect, the Pumas quarry is the location  
660 where, to our knowledge, the thickest pile of young basaltic lava fed by a single eruption has  
661 been found in Mexico. Such continuous vertical exposure provides an excellent opportunity  
662 to study changes in the properties of basaltic lava at both small spatial and short temporal  
663 scales. Samples from this site have thus been used to assess the consistency of paleomagnetic  
664 measurements (Alva-Valdivia et al. 2005) and a study of lava’s chemical variations at that  
665 location is ongoing, with the aim to shed light on processes taking place during such  
666 monogenetic eruptions. This site is also important for interpreting the mode of growth of the

667 lavas by the inflation process (or swelling) that creates the specific internal structure of the  
668 lava (vesiculated crust at the base and top, dense core) and the formation of the sheet lobes  
669 and tumuli that have planar and uplifted geometries, respectively. These features that are  
670 exceptionally well displayed by the quarry walls, are typical of pahoehoe lavas observed in  
671 a wide range of settings and diagnostic of long-lived, far-reaching lava flows (Self et al.  
672 1998). They are hence significant for the study and understanding of effusive basaltic  
673 eruptions worldwide.

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

686

#### 687 **Other sites with similar scientific value**

688 There are many other places in UNAM where the typical internal structure of inflated  
689 pahoehoe is displayed, although at smaller scale than at the Pumas quarry. A site at the main

690 entrance of the campus displays a long and continuous vertical cut in a sheet lobe (ID5 in  
691 Palacio and Guilbaud 2015). There are also deep cuts along the northwestern side of the  
692 Olympic Stadium, in the “Casa Club del Académico”, and along Insurgentes, the main  
693 avenue that crosses the University. These sites are extensively used for rock climbing,  
694 including by professionals for training, another interesting use of vertical lava outcrops.

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

701

702

### 703 **5. State of conservation and risk of degradation of the proposed geosites**

704

705 Exposures of the Xitle volcano and its lavas are threatened with serious damage to complete  
706 disappearance, due to the uncontrolled expansion and densification of Mexico City in the  
707 southwestern part of the Mexico basin (Cano-Santana et al. 2006; Hernández-Robles 2019).  
708 In most urbanized parts of the lava field, the original landform is hardly recognizable, and  
709 rock outcrops are scarcely found, being completely covered by concrete. Despite their  
710 significance, all the geosites described in this paper show signs of degradation and constant  
711 threats from building over. Despite being part of conservation land (“suelo de conservación”,  
712 GDF 2012), the vent area is invaded by illegal settlements that cover an increasing part of



713 the area and damage irreversibly the volcanic products and associated biodiversity (Pezzoli  
714 2000; Aguilar and Santos 2011). During the last decades, the Cuicuilco archeological site  
715 was severely fragmented and partly destroyed in order to build a large commercial center, as  
716 well as governmental and commercial offices. Only recently, a program was initiated to  
717 restore part of it, but the destruction is irreversible (Pérez-Galicia and Pérez-Campuzano  
718 2015).

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

731

## 732 **6. Quantitative assessment**

733

734 To evaluate quantitatively the significance of the proposed geosites and compare their  
735 scientific, educational and touristic values, we applied the assessment method of Brilha

736 (2016), and show a summary of the results in Table 3. Specific methods have been developed  
737 for assessing the touristic values of urban geomorphosites (Clivaz and Reynard 2018; Pica et  
738 al. 2016, 2017), nevertheless, we argue that the more general method of Brilha (2016) allows  
739 a useful comparison of the Xitle geosites and effectively highlights the elements that impact  
740 negatively on their value and may be improved in the future. Besides, the Xitle geosites are  
741 all visible landforms whose value assessment does not require considering abundant  
742 archaeological and historical data, such as for deeply transformed, “invisible”  
743 geomorphosites in European cities (Nistor et al. 2017; Pica et al. 2017; Ticar et al. 2017;  
744 Clivaz and Reynard 2018).

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

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

758           It is noteworthy that some criteria had identical values for all 4 geosites. They all had  
759 the highest grade for representativeness, integrity, association with other values, observation  
760 conditions, and didactic potential, which is consistent with our purpose (they were selected  
761 precisely for these criteria). However, they all have low scenery value, given that the criterion  
762 used by this method is the promotion of the sites by touristic campaigns that are non-existent  
763 for natural sites in Mexico City. Nonetheless, the city setting promotes their proximity to  
764 large accommodation facilities and recreational areas, a high population density, and high  
765 economic level (compared to national average). The way the geoheritage value of the geosites  
766 could be enhanced is discussed in section 7.4 below.

767

768

## 769           **7. Benefits of the Xitle geoheritage to the city**

770

771 Based on our study of the Xitle geoheritage, we review more extensively its relevance for  
772 wider issues such as nature preservation and sustainability (7.1), social equity (7.2), and  
773 awareness on natural hazards (7.3). We finally expose an existing initiative led by academics  
774 at UNAM to promote this geoheritage and point to avenues for an amplification of these, to  
775 guarantee the preservation of the sites and foster their sustainable use by the city (7.4).

776

### 777           **7.1 Relevance for nature preservation, ecosystem services and sustainability in the** 778           **context of urban development**

779 Geosites are celebrations of nature and its link with humanity. In cities, nature tends to  
780 disappear under the pressure for construction and economic growth. Geosites are hence

781 crucial for preserving remnants of natural elements in an otherwise sterile environment, and  
782 should be considered as a key component for conservation (Gordon et al. 2018). Xitle  
783 geosites are particularly important in that respect, for the close relationship that exists  
784 between their geodiversity and the associated diversity in soils (pedodiversity) and flora and  
785 fauna (biodiversity). The Mexico Basin has suffered extremely rapid and destructive urban  
786 growth during the last 50 years, and the preservation of the last remains of fauna and flora  
787 that is endemic of this region and unique in the world strongly relies on the conservation of  
788 the Xitle lavas, whose elevated diversity in morphology and vesicularity creates a wide range  
789 of microhabitats that host a considerable number of species (e.g., Estañol-Tecuatl and Cano-  
790 Santana 2017).

791 Moreover, Reynard et al (2017) argues that, in addition to being sites of interest for society  
792 that are located within the limits of the urban space (*lato sensu* definition), urban geosites  
793 can be places that help understanding the interaction between geological forces and urban  
794 development (*stricto sensu* definition). The Xitle geosites are a good example of urban  
795 geosites *stricto sensu*, as they remarkably conserve the testimony of the long-lasting  
796 interaction of volcanic activity with human development, during a ca. 2,000 years period  
797 stretching from the eruption until today. Xitle lavas initially destroyed an early, large human  
798 settlement in the basin, creating a strong link between the geoheritage and the archaeological  
799 heritage of this region. Then, they slowed the expansion of the city because they were  
800 difficult to build on, hence controlling the pattern of urban development in the southwestern  
801 corner of the basin (note that main avenues surround the lava field's border, Fig. 4). Now  
802 they host the last natural areas and the country's main university, providing multiple  
803 ecosystem services to the city (habitat provision for endemic plants and animals, mitigation

804 of flooding and damage by earthquakes, source of building and ornamental stones, water  
805 filtration and storage, recreation, outdoor sport, culture, identity, science knowledge and  
806 education). The conservation of the open lava surface is particularly important for  
807 sustainability as its destruction through its coverage by cement, constructions or  
808 impermeable, exotic soils reduces drastically its capacity of infiltration, and hence preserving  
809 the original landforms is important for preserving water resources that may be fundamental  
810 in the future (Canteiro et al. 2019; Zambrano et al. 2019). In the UNAM campus alone, the  
811 cost of conserving open green areas with exotic tree species and lawn is very large in terms  
812 of water for irrigation, whereas the natural ecosystem sustains itself through the natural  
813 capacity of the lava to store water and the low requirements of water by endemic plants  
814 (Camarena-Berruecos 2010). In conclusion, the Xitle geoheritage should be explicitly  
815 included in natural conservation plans and urban planning strategies for the southwestern  
816 corner of the Mexico Basin, because of the multiple benefits it provides for the area.

817

## 818 **7.2 Relevance for providing well-being and reducing social inequalities**

819 Nature preservation in cities strongly depends on urban planning and associated construction  
820 rules. These can vary spatially within cities, especially in countries with high inequalities  
821 such as Mexico. The preservation status of outcrops and associated biological elements in  
822 the urbanized part of the Xitle lava field varies widely, reflecting the economic and social  
823 segmentation of the city. Rich neighborhoods (e.g. Jardines del Pedregal) preserve outcrops  
824 and associated vegetation in nice parks, gardens and, occasionally, caves in house basements,  
825 while in poor neighborhoods (e.g. Santa Ursula, Santo Domingo), every bit of lava is covered  
826 by concrete, vegetation is sparse and almost all non-native (Fig. 10), and the few remaining

827 outcrops are used as dumps. The origin of such dichotomy is historical, as rich districts were  
828 designed by architects and engineers, whereas poor neighborhoods grew chaotically, from  
829 illegal settlements. These initial disparities were then amplified by the limited public funding  
830 to restore and maintain green areas. Hence, the remaining state of the lava outcrops in the  
831 city and quality of the environment (lamentably) reflects the distribution of economic wealth,  
832 amplifying social inequalities.

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

844

### 845 **7.3 Relevance for mitigation and education on natural hazards**

846 Nature under pressure increases dramatically the impact scale of natural hazards. At the time  
847 of writing, the Covid-9 pandemic is putting under lockdown at hundreds of millions of people  
848 worldwide, with tragic social, economic, and political impacts. Although this event has  
849 complex, multi-factual sources that will require years of investigation to untangle, it may be

850 considered as an example of a small natural hazard (a virus hosted in an animal) that turned  
851 into a global disaster, partly due to the increasing interference of humans on wildlife and the  
852 environment (e.g., Bonilla-Aldana et al. 2020). Geosites are ways we can, as a community,  
853 restore links between society and nature, and acknowledge its relevance for our past, present  
854 and future. It also allows to promote a better communication and thrust between the  
855 population and the scientific community, which would allow, in the long term, to better  
856 mitigate hazards.

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

873

874 **7.4 Local sustainable development and geoeeducation through geoheritage: Ongoing**  
875 **initiatives and future opportunities**

876

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

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

891         Another clue to promote urban heritage is to involve local university and educational  
892 centers that are located near the geoheritage elements. As highlighted above, the UNAM  
893 campus is a key area for the preservation of Xitle geoheritage. The university is also the main  
894 research and education hub in the country. It should hence have a leading role in promoting  
895 such heritage. The two UNESCO Geoparks in Mexico (Comarca Minera and Mixteca Alta)



896 that were nominated in 2007, were initiated by UNAM-based research groups and arose from  
897 the joint participation with municipal authorities, ejidatarios (managers of communal lands),  
898 and the local population. The geoparks continue to receive UNAM support through research  
899 projects, but they are managed by locals who are also the main beneficiaries.

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

918 teaching is currently done by students. Didactic material incorporating geological  
919 information should also be developed and published formally.

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

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

941 architecture and arts, as well as UNAM authorities, the local government (Delegación de  
942 Coyoacán) and the government of Mexico City.

943

## 944 **8. Conclusions**

945

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

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

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

961 Urban geoheritage commonly lacks visibility, which could be improved by valuing  
962 the cultural values associated to the sites, and engaging local actors such as educational  
963 centers. Existing educational projects such as the Geopedregal at the national university

964 should be consolidated and used as a basis to develop community-based projects at other  
965 sites. Initiatives such as creating an urban geopark or converting the UNESCO World  
966 Heritage cultural site of the university campus to a mixed cultural-natural site, should be  
967 considered as ways to ensure the conservation of the Geoheritage and its multiple benefits to  
968 the city.

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

972

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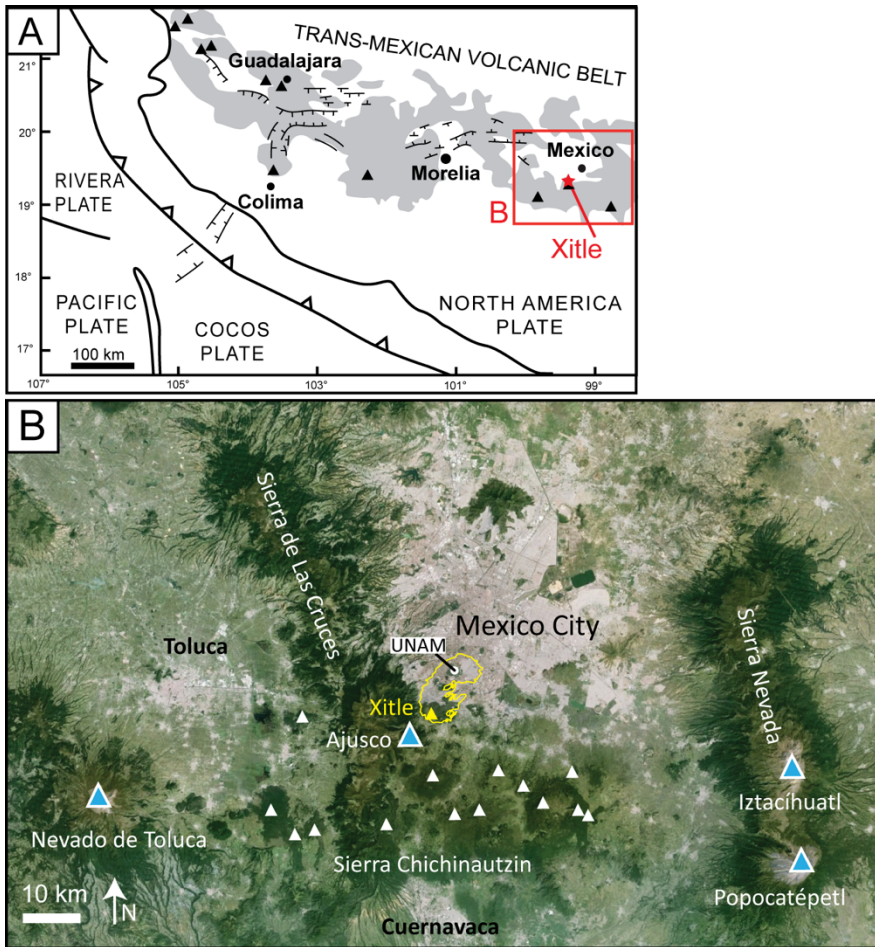
974 **Electronic Appendix**

975

976 Slide with pictures of activities in the Geopedregal site.

977

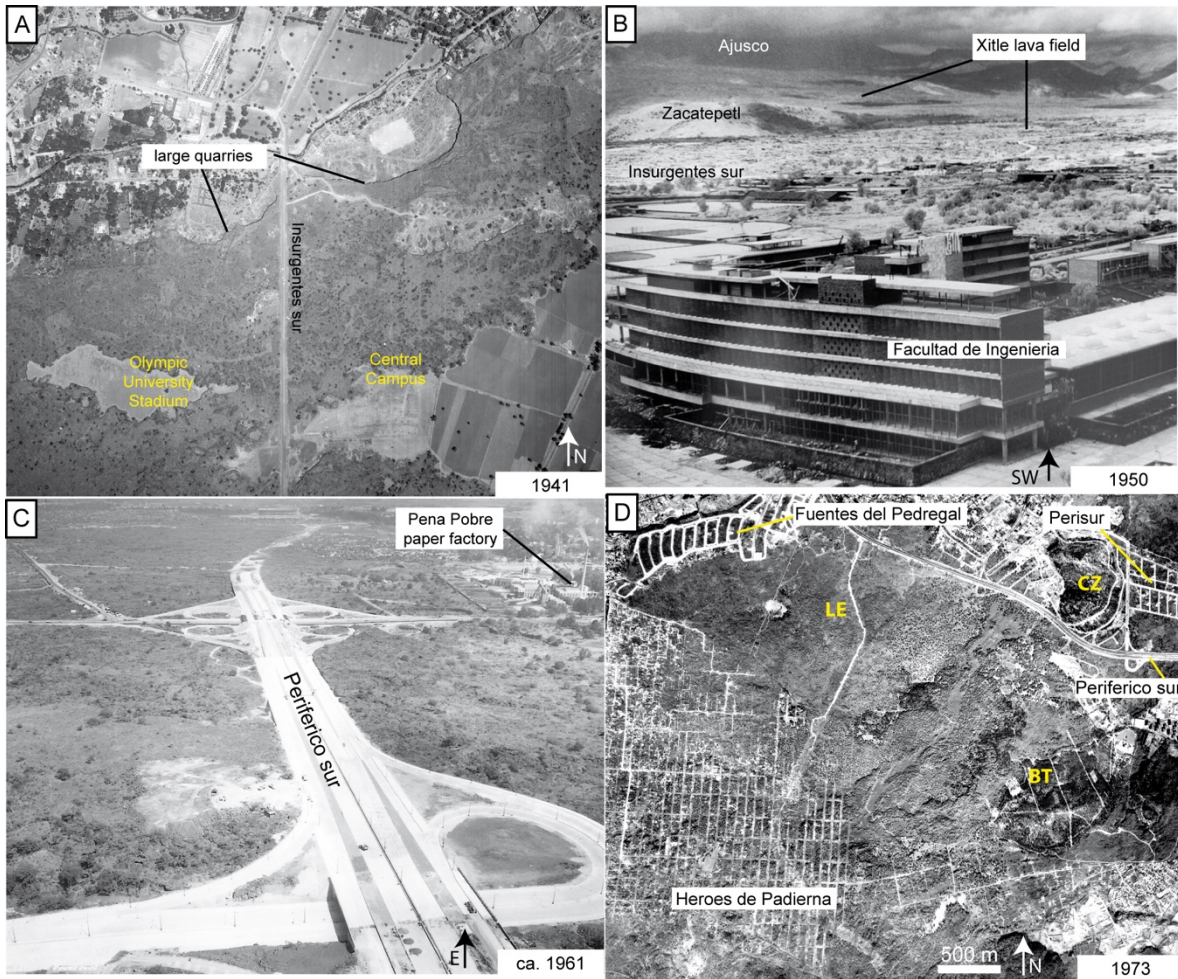
978 **Figures**



979

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

989



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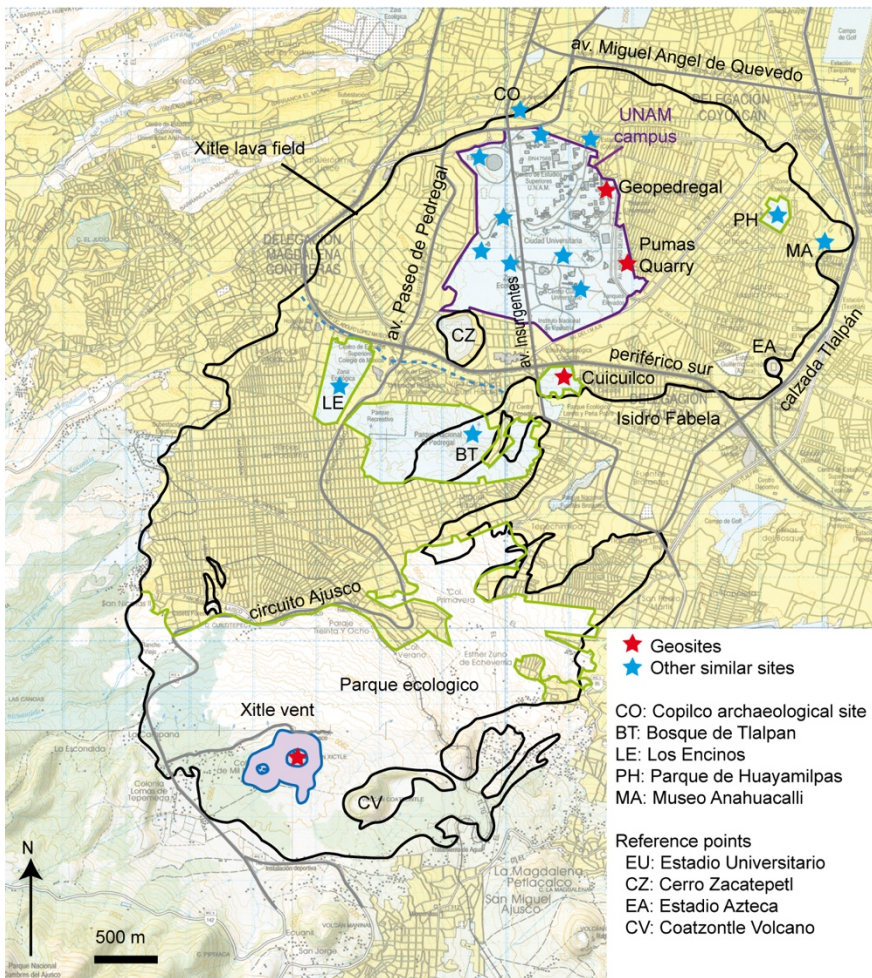
991 **Fig. 2** A. Vertical aerial photo of the present location of the central part of the UNAM campus  
 992 in 1941 (FICA foundation). The location of the agricultural fields where the Olympic  
 993 University stadium and the Central Campus were constructed few years later is indicated.  
 994 Note also the concave shape of large quarries into the lavas that are now urbanized. The entire  
 995 area is virtually unrecognizable in today's photographs. B. Oblique aerial photo of the first  
 996 university building constructed over the lava field (taken from Salas Portugal, 2006). C.  
 997 Oblique aerial photo of the southern peripheric road of Mexico City (Periferico sur), just after  
 998 its construction on the lavas in 1961 (provided by A. Lentz). D. Vertical aerial photo of the  
 999 lava field to the south of the Periferico sur in 1973. Note the road tracks of an exclusive  
 1000 residential area (Fuentes del Pedregal) and a mall (Perisur) in the northern part, and a more

1001 extensive popular area (Heroes de Padierna) to the southeast. The area is now entirely  
1002 urbanized, except for few remaining patches including the Los Encinos area (LE), the summit  
1003 of Cerro Zacatepetl hill (CZ), and the Bosque de Tlalpan (BT)  
1004



1005  
1006 **Fig. 3** A. Detail of a painting on the facade of the town hall building of Tlalpán featuring pre-  
1007 hispanic people fleeing the Xitle eruption. B. Photograph of a vertical cut into a sheet lobe  
1008 along the Insurgentes avenue in UNAM. Men point to a vertical line of holes drilled for  
1009 paleomagnetism studies. C. Photograph of the Xitle cone and proximal lavas covered by a

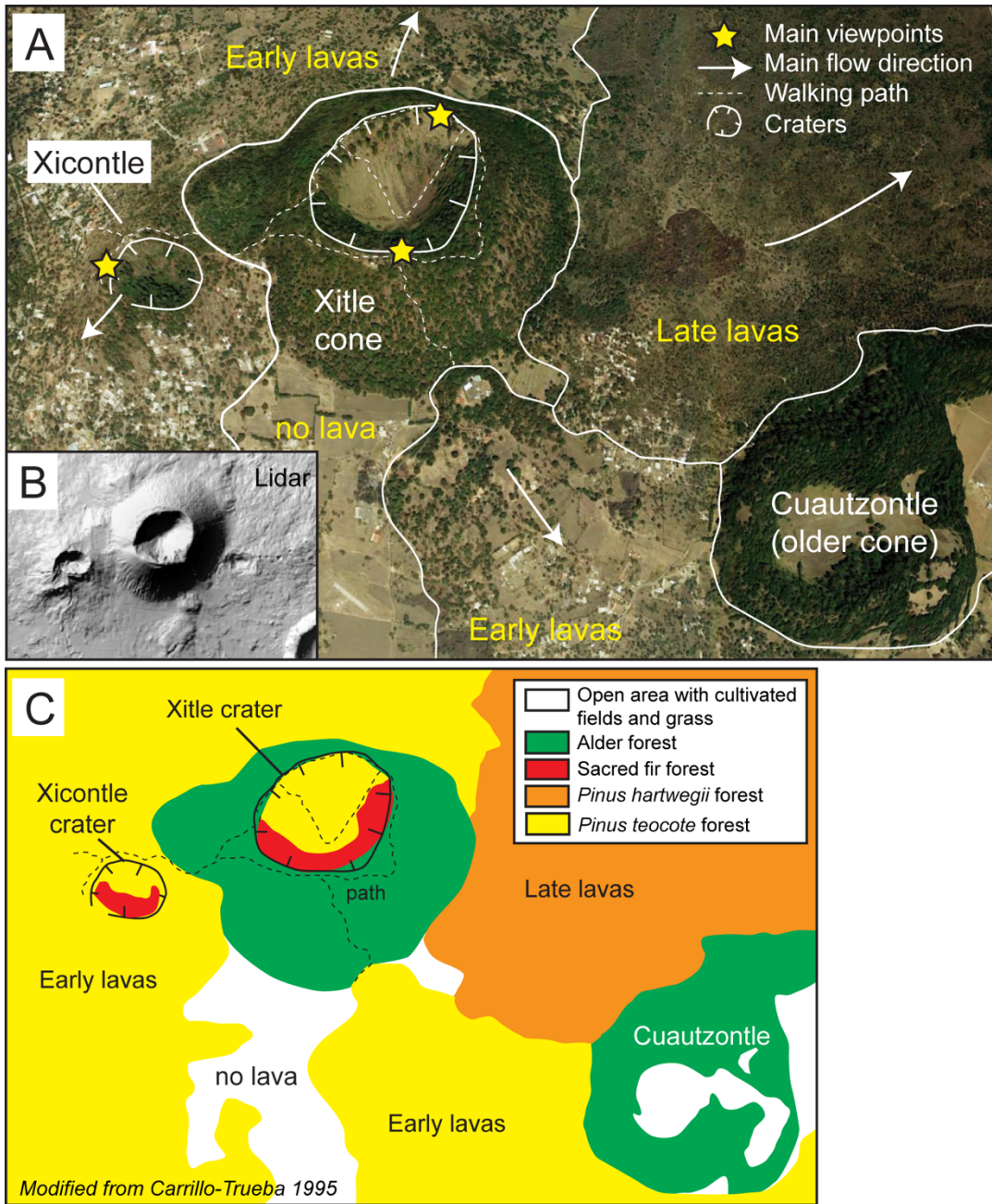
1010 pine tree forest, from the south. D. Photograph of the vegetated lava flow preserved in the  
 1011 Cuicuilco archaeological site. Note the Xitle cone and Ajusco stratovolcano in the distance.  
 1012 E. Photograph of the Anahuacalli museum built by Diego Rivera to expose its collection of  
 1013 archaeological pieces. It is made entirely by stones from the Xitle lava and preserves a patch  
 1014 of the lava field around it  
 1015



1016  
 1017 **Fig. 4** General map of the Xitle cone and lava flow field with the location of important  
 1018 reference points in the city and the sites described in the text. Note that the topographic map  
 1019 used as background indicate in yellow the constructed areas, while “natural” areas are left in

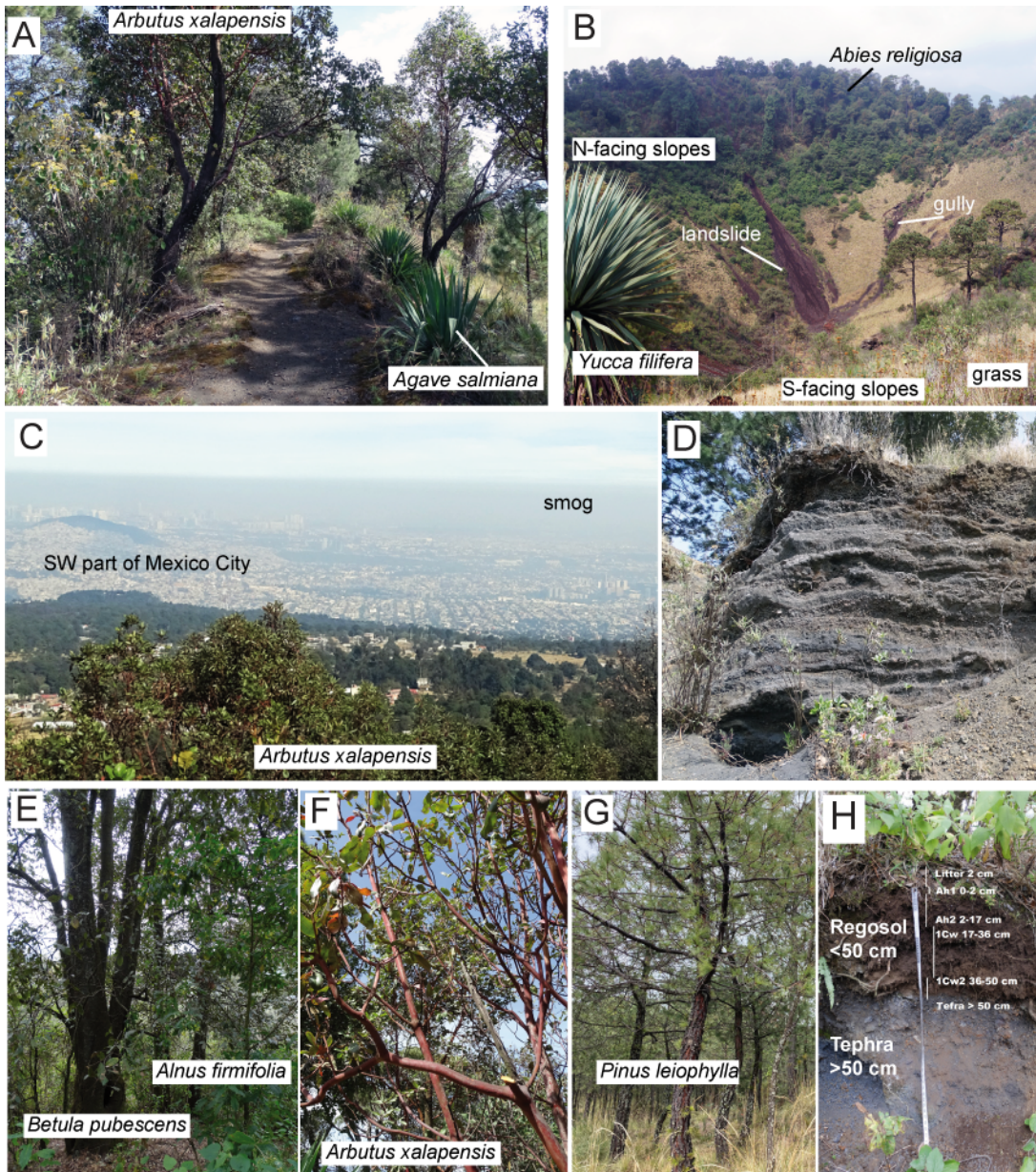


1020 white. Most of these correspond to places where the lava surface and its vegetation can still  
 1021 be observed, although illegal settlements are commonly found and deteriorate the sites  
 1022



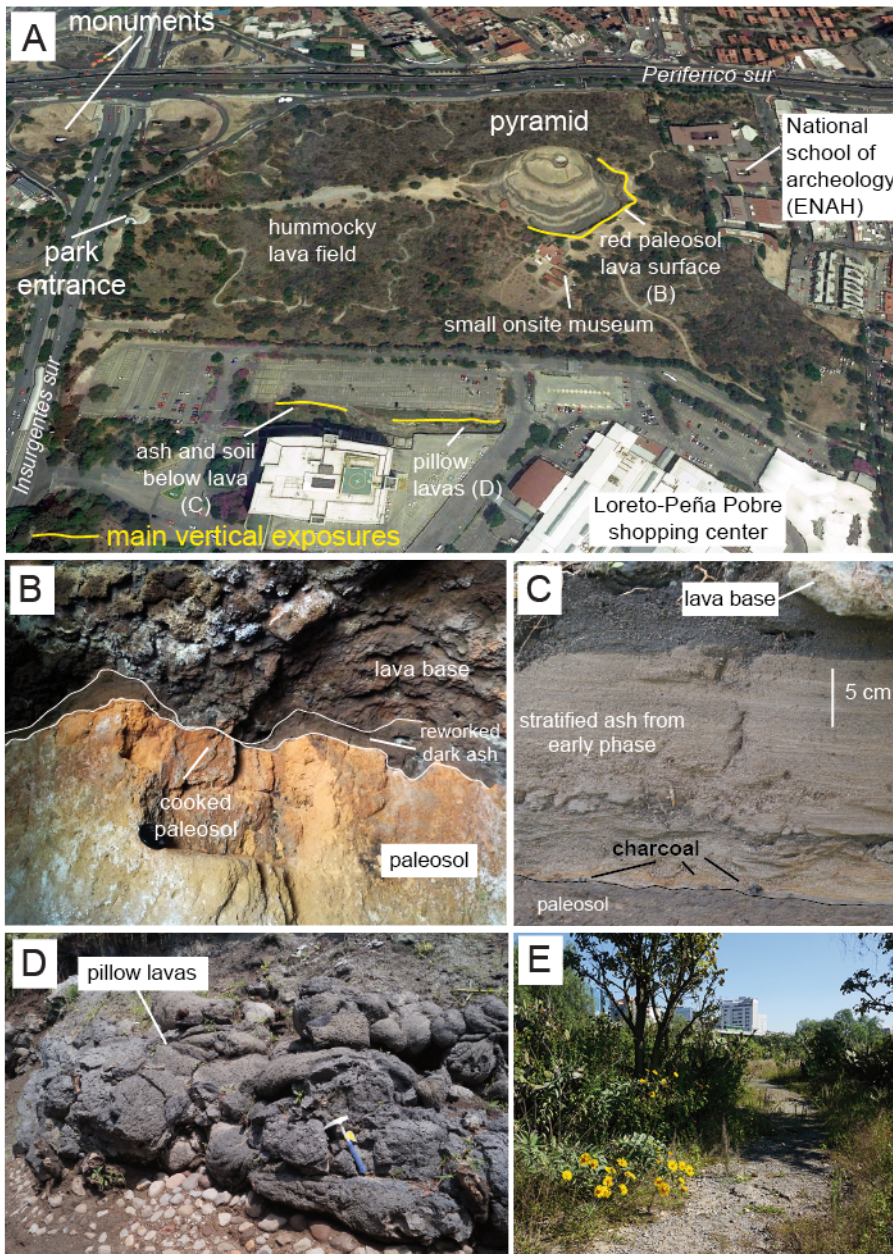
1023  
 1024 **Fig. 5** Vent area geosite: Maps. A. Cartography of main volcanic elements along with the  
 1025 walking paths and location of early- and late-formed lavas on a slightly-inclined view of

1026 satellite images draped over an elevation model from Google Earth. B. Shaded relief from a  
 1027 5-m resolution digital elevation model that shows clearly the shape and inner crater of the  
 1028 main scoria cone and the Xicotle spatter-lava cone. C. Vegetation cover map modified from  
 1029 Carrillo-Trueba (1995), and drawn from satellite images and field observations. See the text  
 1030 for more explanation  
 1031



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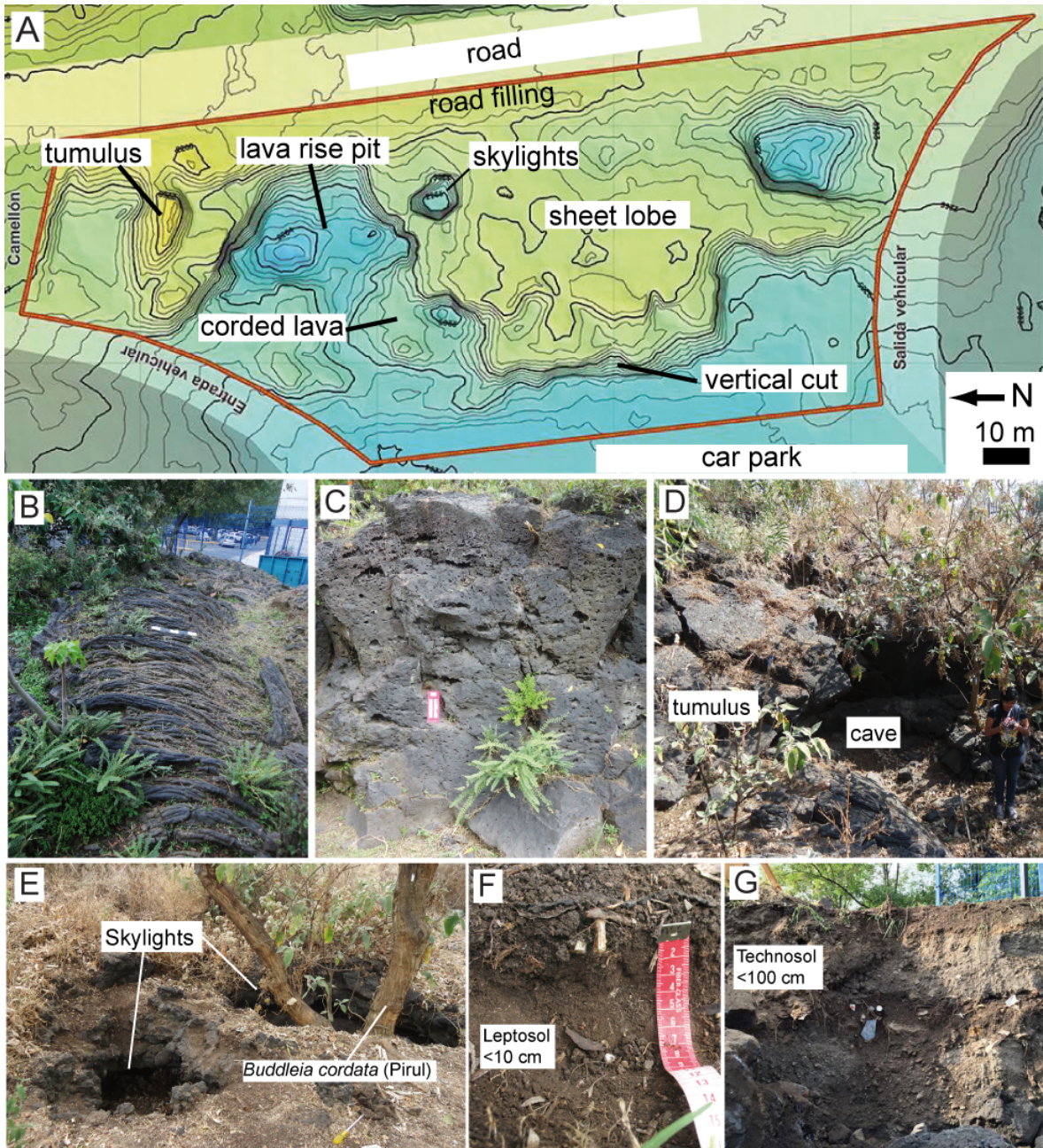
1033 **Fig. 6** Vent area geosite: Pictures. A. Photograph showing the path surrounding the crater  
1034 rim of the Xitle cone on its west side and the associated vegetation pattern. B. Photograph  
1035 taken from the south part of the crater rim, looking north, showing the N- and S-facing crater  
1036 slopes and their contrast in vegetation and erosional pattern. C. Photograph on the view from  
1037 the southern part of the Xitle crater rim looking N, showing the southern part of Mexico City  
1038 covered by smog. D. Photograph of a ca. 1 m deep exposure into the outermost layers of the  
1039 Xitle cone that consist of layers of tephra, from ash to lapilli in size. E, F, G. Photographs of  
1040 important tree species on the Xitle cone. H. Photograph of the soil section described in detail  
1041 in Table 2 and in the text  
1042



1043

1044 **Fig. 7** Cuiculco geosite. A. Cartography of main anthropic, archeologic and volcanic  
 1045 elements on a slightly-inclined view of satellite images draped over an elevation model from  
 1046 Google Earth. Capital letters indicate the location where the subsequent pictures were taken.  
 1047 B. Photograph taken inside the tunnel excavated below the lavas, that shows the paleosol,  
 1048 ash layer and lava base. C. Photograph of a finely stratified, 17-cm-thick ash layer found just  
 1049 below the lava, at an outcrop located next to a building in the commercial center. Note the

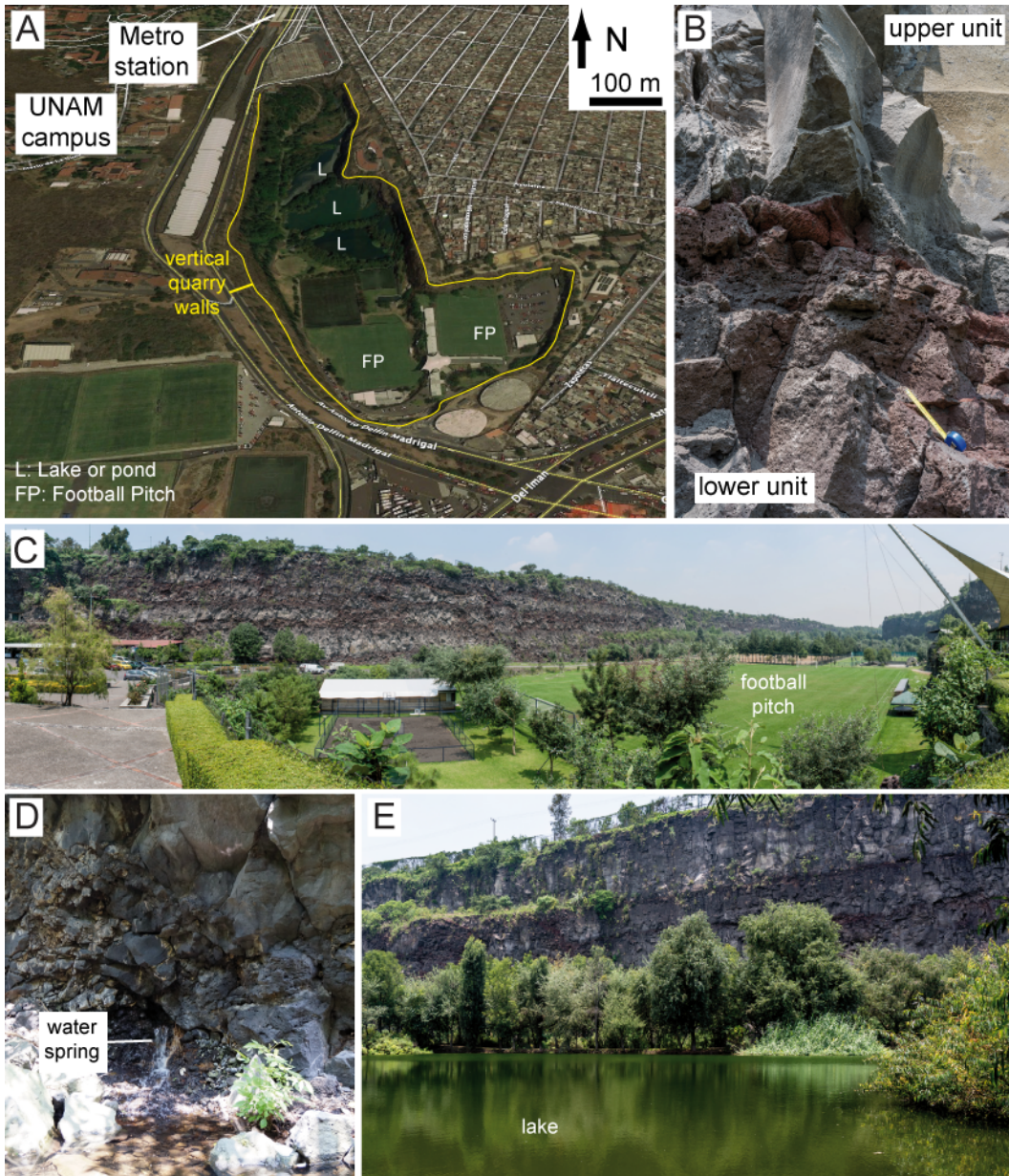
1050 tiny dark charcoal bits found in the lowermost ash layer. Similar fragments were dated using  
1051 radiocarbon by Siebe (2000) to obtain the age of the eruption. D. Rounded pillow-type lavas  
1052 exposed along the ground level of a carpark in the commercial center. Archeologists obtained  
1053 the permission in late 2018 to study this area in details because of the imminent occurrence  
1054 of major building works. E. Photograph taken at the start of one of the pedestrian paths that  
1055 cross the lava field surrounding the pyramid. Note the pleasantness of the path provided by  
1056 the vegetation and the slightly irregular ground. One of the tall buildings constructed along  
1057 the “Periferico Sur” avenue is visible in the background, highlighting the close vicinity of  
1058 one of the busiest roads in Mexico City.



1059

1060 **Fig. 8** Geopedregal geosite. A. Topographic map showing the distinct volcanological  
 1061 elements described in the text. Adapted from figure made by P. Leautaud. B. Photograph of  
 1062 the corded lava features. C. Photograph of the vertical section across the lava that displays  
 1063 the typical upward increase in vesicle density and decrease in vesicle size that is observed in  
 1064 pahoehoe lavas and is symptomatic of a growth by inflation. Note also the vegetation growing

1065 in the small fractures (cooling joints) in the lava. D. Photograph of the oval-shaped tumulus  
1066 that borders the site and present a lateral cave that is occupied by bats and other local fauna.  
1067 E. Photograph of the jointed skylights that formed on the sheet lobe. Note the relatively large  
1068 Tepozán tree that grew from inside the cavity. F. Photograph of the typical type of soil that  
1069 forms locally on the lava (see text and Table 2 for description). G. Photograph of the  
1070 anthropogenic Technosol soil observed on top of the lava, along the road. Note the  
1071 occurrence of man-made objects within the soil (mostly made of plastic) and gravel



1072

1073 **Fig. 9** Pumas quarry geosite. A. Map of the Pumas quarry or Cantera Poniente. Note its  
 1074 location between the UNAM campus to the west, and the densely-populated Santo Domingo  
 1075 popular borrow to the east. B. Contact between two flow units exposed along the quarry  
 1076 walls. Note the reddish (oxidized) vesicular upper crust of the lower unit and denser, light-  
 1077 gray internal core of the upper unit. C. Panoramic photograph of the site that shows the largest  
 1078 football pitch and the quarry walls, as well as the surrounding green areas. D. Photograph of



1079 a water spring that can be seen along a walking path at the base of the highest quarry wall  
1080 along the western border of the site. E. Photograph of the lake and the eastern quarry wall in  
1081 the background, taken from a walking path. Note the pleasant green setting and peculiar  
1082 vegetation



1083  
1084 **Fig. 10** Pictures taken using google street view, of two districts, a poor (Santa Ursula) and a  
1085 rich (Jardines del Pedregal) constructed over the Xitle lava field. Note the differences in the  
1086 environment (see text for more details).  
1087

1088 **References**

- 1089 Aguilar AG, Santos C (2011) Informal settlements' needs and environmental conservation  
1090 in Mexico City: An unsolved challenge for land-use policy. *Land Use Policy* 28(4): 49-  
1091 662. <https://doi.org/10.1016/j.landusepol.2010.11.002>
- 1092 Agustín-Flores J, Siebe C, Guilbaud MN (2011) Geology and geochemistry of Pelagatos,  
1093 Cerro del Agua, and Dos Cerros monogenetic volcanoes in the Sierra Chichinautzin  
1094 Volcanic Field, south of México City, *J Volcanol Geoth Res* 201:143–162. DOI:  
1095 10.1016/j.jvolgeores.2010.08.010
- 1096 Alva-Valdivia LM (2005). Comprehensive paleomagnetic study of a succession of Holocene  
1097 olivine-basalt flow: Xitle Volcano (Mexico) revisited. *Earth planets and space* 57(9):  
1098 839-853
- 1099 Aragón-Durand F (2007) Urbanisation and flood vulnerability in the peri-urban interface of  
1100 Mexico City. *Disasters* 31(4):477-494. [https://doi.org/10.1111/j.1467-  
1101 7717.2007.01020.x](https://doi.org/10.1111/j.1467-7717.2007.01020.x)
- 1102 Arce JL, Layer PW, Lassiter JC, Benowitz JA, Macías JL, Ramírez-Espinosa J (2013)  
1103 <sup>40</sup>Ar/<sup>39</sup>Ar dating, geochemistry, and isotopic analyses of the quaternary Chichinautzin  
1104 volcanic field, south of Mexico City: implications for timing, eruption rate, and  
1105 distribution of volcanism. *Bull Volcanol* 75:774
- 1106 Arce JL, Muñoz-Salinas E, Castillo M, Salinas I (2015) The ~2000 yr BP Jumento volcano,  
1107 one of the youngest edifices of the Chichinautzin Volcanic Field, Central Mexico. *J  
1108 Volcanol Geoth Res* 308:30-38
- 1109 Arnold JR, Libby WF (1951) Radiocarbon dates. *Science* 113(2927):111-120

1110 Badilla-Cruz RR (1977) Estudio petrológico de la lava de la parte noreste del Pedregal de  
1111 San Ángel, D.F. Bol Soc Geol Mex 38:40-57

1112 Bloomfield K (1975) A late-Quaternary monogenetic volcano field in central Mexico. Geol  
1113 Rundsch 64:476-497

1114 Bonilla-Aldana DK, Dhama K, Rodriguez-Morales AJ (2020) Revisiting the one health  
1115 approach in the context of COVID-19: a look into the ecology of this emerging disease.  
1116 Adv Anim Vet Sci, 8(3), 234-237.

1117 Boothroyd A, McHenry M (2019) Old processes, new movements: the inclusion of  
1118 geodiversity in biological and ecological discourse. Diversity 11(11):216.  
1119 <https://doi.org/10.3390/d11110216>

1120 Brilha J (2016) Inventory and Quantitative Assessment of Geosites and Geodiversity Sites:  
1121 a Review. Geoheritage 8(2):119-134. doi: 10.1007/s12371-014-0139-3

1122 Brilha J, Gray M, Pereira D I, Pereira P (2018) Geodiversity: An integrative review as a  
1123 contribution to the sustainable management of the whole of nature. Environ Sci Policy  
1124 86:19-28

1125 Camarena-Berruecos P (2010) Xerojardinería. Guía para el diseño de los jardines de Ciudad  
1126 Universitaria. Universidad Nacional Autónoma de México, Mexico City, 92 pp

1127 Campillo M, Gariel JC, Aki K, Sánchez-Sesma FJ (1989) Destructive strong ground motion  
1128 in Mexico City: Source, path, and site effects during great 1985 Michoacán earthquake.  
1129 Bull Seismol Soc Am 79(6):1718-1735

1130 Cano-Santana Z, Pisanty I, Segura S, Mendoza-Hernández PE, León-Rico R, Soberón J, et  
1131 al (2006) Ecología, conservación, restauración y manejo de las áreas naturales y  
1132 protegidas del Pedregal del Xitle. In : Oyama K, Castillo A (eds) Manejo, conservación

1133 y Restauración de Recursos naturales en México, UNAM-Siglo XXI, Mexico City, pp  
1134 203-226

1135 Canteiro M, Olea S, Escolero O, Zambrano L (2019) Relationships between urban aquifers  
1136 and preserved areas South of Mexico City. *Groundw Sustain Dev* 8:373-380

1137 Cañon-Tapia E, Walker GPL, Herrero-Bervera E (1995) Magnetic fabric and flow direction  
1138 in basaltic Pahoehoe lava of Xitle Volcano, Mexico: *J Volcanol Geotherm Res* 65:249-  
1139 263

1140 Cañon-Tapia E, Walker GPL, Herrero-Bervera E (1996). The internal structure of lava flows-  
1141 insights from AMS measurements I: Near-vent aa: *J Volcanol Geotherm Res* 70:21-36

1142 Carrillo-Trueba C (1995) El Pedregal de San Ángel, Universidad National Autonoma de  
1143 Mexico, Mexico City

1144 Castellanos-Vargas I, García-Calderón NE, Cano Santana Z (2017) Procesos físicos del suelo  
1145 en la reserva ecológica del Pedregal de San Ángel de Ciudad Universitaria: atributos  
1146 para su conservación. *Terra Latinoamericana* 35(1):51-64

1147 Clivaz M, Reynard E (2018) How to integrate invisible geomorphosites in an inventory: A  
1148 case study in the Rhone River valley (Switzerland). *Geoheritage* 10(4) :527-541

1149 Coordinación de Proyectos Especiales, UNAM (2005) Technical file for the nomination of  
1150 campus central de la Ciudad Universitaria de la UNAM for the Inscription in the  
1151 Unesco World Heritage List, Mexico City.

1152 Córdova C, Martin del Pozzo AL, Camacho JL (1994) Palaeolandforms and Volcanic Impact  
1153 on the Environment of Prehistoric Cuicuilco, Southern Mexico City. *J Archaeol Sci*  
1154 21(5):585-596

1155 Cummings B (1926) Cuicuilco and the Archaic culture of Mexico: *Scientific Monthly*,  
1156 23:289-304

1157 Del Monte M, Fredi P, Pica A, Vergari F (2013) Geosites within Rome City center (Italy): a  
1158 mixture of cultural and geomorphological heritage. *Geografia Fisica e Dinamica*  
1159 *Quaternaria* 36(2):241-257

1160 Del Moral R, Grishin SY (1999) Volcanic disturbances and ecosystem recovery. In: Walker  
1161 LR (Ed) *Ecosystems of disturbed Ground*, Elsevier, Amsterdam, pp 137-160

1162 Delgado H, Molinero R, Cervantes P, Nieto-Obregón J, Lozano-Santa Cruz R, Macías-  
1163 González HL, Mendoza-Rosales C, Silva-Romo G (1998) Geology of Xitle volcano in  
1164 southern Mexico-City, A 2000 year-old monogenetic volcano in an urban area. *Revista*  
1165 *Mexicana de Ciencias Geológicas* 15 (2):115-131

1166 Eakin H, Lerner AM, Manuel-Navarrete D, Aguilar BH, Martínez-Canedo A, Tellman B,  
1167 Bojórquez-Tapia L (2016) Adapting to risk and perpetuating poverty: household's  
1168 strategies for managing flood risk and water scarcity in Mexico City. *Environ Sci*  
1169 *Policy* 66:324-333

1170 Eiser JR, Bostron A, Bruton I, Johnston DM, McClure J, Paton D, van de Pligt J, White MP  
1171 (2012) Risk interpretation and action: A conceptual framework for responses to natural  
1172 hazards. *Intern J Disaster Risk Reduction* 1:5-16

1173 Estañol-Tecuatl F, Cano-Santana Z (2017) Recovery of basalt substrate for xeric scrub  
1174 restoration in a lava field in Mexico City. *Ecological Restoration* 35(1):41-51.

1175 Fassoulas C, Watanabe M, Pavlova I, Amorfini A, Dellarole E, Dierickx F (2018) UNESCO  
1176 Global Geoparks: living laboratories to mitigate natural induced disasters and  
1177 strengthen communities' resilience. In: Antronico L, Marincioni F (Ed) *Natural*  
1178 *Hazards and Disaster Risk Reduction Policies, Geographies of the Anthropocene*, pp  
1179 175-285

1180 Flores-Estrella H, Yussim S, Lomnitz C (2007) Seismic response of the Mexico City Basin:  
1181 A review of twenty years of research. *Natural Hazards* 40(2):357-372.  
1182 <https://doi.org/10.1007/s11069-006-0034-6>

1183 Gamio M (1920) Las excavaciones del Pedregal de San Angel y la cultura arcaica del Valle  
1184 de México. *American Anthropologist* 22(2):127-143

1185 GDF (Gobierno del Distrito Federal) (2012) Atlas geográfico del suelo de conservación del  
1186 Distrito Federal. Secretaría del Medio Ambiente, Procuraduría Ambiental y del  
1187 Ordenamiento Territorial del Distrito Federal, México, D.F.

1188 González R, Estrada M, Orellana A, Bueno I, Segura S (2016) Saving Islands Within a City.  
1189 Available online at: <https://it.cornell.edu/> (accessed March 17, 2019)

1190 González S, Pastrana A, Siebe C, Duller G (2000) Timing of the prehistoric eruption of Xitle  
1191 Volcano and the abandonment of Cuicuilco Pyramid, Southern Basin of Mexico. In:  
1192 McGuire et al (Eds) *The archaeology of geological catastrophes*, Geological Society,  
1193 London, Special publications 171:205-224

1194 Gordon JE, Crofts R, Díaz-Martínez E (2018) Geoheritage conservation and environmental  
1195 policies: retrospect and prospect. In: Brilha J, Reynard E (eds) *Geoheritage*  
1196 *Assessment, Protection and Management*, Elsevier, Amsterdam, Chapter 12, pp 213-  
1197 235

1198 Górska-Zabielska M, Zabielski R (2017) Potential values of urban geotourism development  
1199 in a small Polish town (Pruszków, Central Mazovia, Poland). *Quaestiones*  
1200 *Geographicae* 36(3):75-86

1201 Gray M (2013) *Geodiversity: Valuing and Conserving Abiotic Nature*, 2nd Edition, Wiley,  
1202 Blackwell. ISBN: 978-0-470-74215-0

1203 Gray M (2018) Geodiversity: the backbone of geoheritage and geoconservation. In : Brilha  
1204 J, Reynard E (Eds) *Geoheritage Assessment, Protection and Management*, Elsevier,  
1205 Amsterdam, pp 13-25. <https://doi.org/10.1016/B978-0-12-809531-7.00001-0>

1206 Guilbaud MN, Arana-Salinas L, Siebe C, Barba-Pingarrón LA, Ortiz A (2015) Volcanic  
1207 stratigraphy of a high-altitude *Mammuthus columbi* (Tlacotenco, Sierra  
1208 Chichinautzin), Central México. *Bull Volcanol* 77:17. DOI:10.1007/s00445-015-0903-  
1209 5

1210 Guilbaud MN, Siebe C (2009) The lava flow-field of the ca. 1670 yrs BP Xitle eruption,  
1211 México: structure and implications for eruption dynamics (abstract). In : Siebe C,  
1212 Guilbaud M-N, Salinas S (Eds) *250 Aniversario del nacimiento del volcán Jorullo en*  
1213 *México: Morelia, Michoacán, Mexico*. Impretei, Mexico City, pp 28-29

1214 Hardoy J, Mitlin D, Satterthwaite D (2013) *Environmental problems in an urbanizing world:*  
1215 *finding solutions in cities in Africa, Asia and Latin America*. Earthscan Publications  
1216 Ltd, London, Washington DC.

1217 Heizer R, Bennyhoff JA (1958) Archaeological investigations of Cuicuilco, Valley of  
1218 Mexico, 1956. *Science* 127:232-233

1219 Heizer R, Bennyhoff JA (1972) Archaeological excavations at Cuicuilco, Mexico, 1957. *Nat*  
1220 *Geog Rep* 1955-1960 :93-104

1221 Hernández-Robles HE (2019) *Dinámica de cambio de uso de suelo y coberturas vegetales en*  
1222 *el derrame de lava del volcán Xitle, Ciudad de México, 1993-2015*. Undergraduate  
1223 thesis, Facultad de Ciencias, UNAM

- 1224 Hon K, Kauahikaua J, Denlinger R, Mackay K (1994) Emplacement and inflation of  
1225 pahoehoe sheet flows, Observations and measurements of active lava flows on Kilauea  
1226 Volcano, Hawaii. *Geol Soc Am Bull* 106:351-370
- 1227 Hough M (2004) *Cities and natural process*. Routledge, London and New York
- 1228 Hubp J, Inbar M, Pastrana A, Flores A, Zamorano J (2001). Interpretation of the geomorphic  
1229 setting of the Cuicuilco basin, Mexico City, affected by the pre-Hispanic eruption of  
1230 the Xitle volcano/Interprétation de l'environnement géomorphologique du bassin de  
1231 Cuicuilco, ville de Mexico, affecté par l'éruption pré-hispanique du volcan Xitle.  
1232 *Géomorphologie: relief, processus, environnement* 7(3) :223-232
- 1233 Jim CY (2004) Green-space preservation and allocation for sustainable greening of compact  
1234 cities. *Cities* 21(4):311-320
- 1235 Jim CY (2013) Sustainable urban greening strategies for compact cities in developing and  
1236 developed economies. *Urban Ecosyst* 16(4):741-761
- 1237 Kelly J (1982) *The Complete Visitor's Guide to Mesoamerican Ruins*. University of  
1238 Oklahoma Press
- 1239 Keszthelyi L (1995) A preliminary thermal budget for lava tubes on the Earth and planets. *J*  
1240 *Geophys Res: Solid Earth*, 100(B10): 20411-20420.
- 1241 Krieger P (2008) *Lecciones inesperadas de Ciudad Universitaria y su reserva ecológica*.  
1242 *Bitácora Universitaria* 18:46-49
- 1243 López-Valdés N (2019) *Secuencia de eventos eruptivos recientes en el sector oriental de la*  
1244 *Sierra Chichinautzin, Centro de México: Distribución, edad y composición química de*  
1245 *lavas y tefras*. Master thesis, UNAM, Mexico



- 1246 Lorenzo-Merino L, Guilbaud MN, Roberge J (2018) The violent-Strombolian eruption of 10  
1247 ka Pelado shield volcano, Sierra Chichinautzin, Central Mexico, Bull Volc 80:27.  
1248 <https://doi.org/10.1007/s00445-018-1208-2>
- 1249 Lot A (2007) Guía ilustrada de la Cantera Oriente. Caracterización ambiental e inventario  
1250 biológico. Coordinacion de la Investigacion Cientifica, Universidad Nacional  
1251 Autonoma de Mexico, Mexico City
- 1252 Lot A, Cano-Santana Z (2009) Biodiversidad del ecosistema del Pedregal de San Ángel.  
1253 Universidad Nacional Autónoma de México, Mexico City
- 1254 Luhr JF, Simkin T (1993) Parícutin: the volcano born in a Mexican cornfield. US Geoscience  
1255 Press Phoenix
- 1256 Mancebo F (2007) Natural hazards and urban policies in Mexico City. Journal of Alpine  
1257 Research. Revue de géographie alpine (95-2):108-118
- 1258 Márquez A, Verma SP, Anguita F, Oyarzun R, Brandle JL (1999) Tectonics and volcanism  
1259 of Sierra Chichinautzin: extension at the front of the Central Trans-Mexican Volcanic  
1260 belt. J Volcanol Geotherm Res 93(1-2):125-150
- 1261 Martín del Pozzo, AL (1982) Monogenetic volcanism in Sierra Chichinautzin, Mexico. Bull  
1262 Volcanol 45:1-24
- 1263 McKeever PJ, Zouros N (2005). Geoparks: Celebrating Earth heritage, sustaining local  
1264 communities. Epis 28(4):274
- 1265 Nistor C, Mihai B, Toma L, Carlan I (2017) Photogrammetric modelling for urban medieval  
1266 site mapping. A case study from Curtea de Argeş, Romania. Quaestiones  
1267 Geographicae 36(3):87-96

- 1268 Ortiz-Zamora D, Ortega-Guerrero A (2010) Evolution of long-term land subsidence near  
1269 Mexico City: Review, field investigations, and predictive simulations. *W Resour Res*  
1270 46(1):W01513. <https://doi.org/10.1029/2008WR007398>
- 1271 Palacio JL, Guilbaud MN (2015) Patrimonio natural de la Reserva Ecológica del Pedregal de  
1272 San Ángel y áreas cercanas: sitios de interés geológico y geomorfológico al sur de la  
1273 Cuenca de México. *Bol Soc Geol Mex* 67(2):227-244
- 1274 Parsons JR (1989) Arqueología regional en la Cuenca de México: una estrategia para la  
1275 investigación futura. *Anales de Antropología* 26:1
- 1276 Pavlova I (2019) Disaster risk reduction at UNESCO Global Geoparks and Biosphere  
1277 Reserves. *Journal of World Heritage Studies*, Special issue 2019, p 73-77  
1278 <http://doi.org/10.15068/00157689>
- 1279 Peña-Ramírez VM, Vázquez-Selem L, Siebe C (2009) Soil organic carbon stocks and forest  
1280 productivity in volcanic ash soils of different age (1835–30,500 years BP) in Mexico.  
1281 *Geoderma* 149(3-4):224-234
- 1282 Pérez-Galicia A, Pérez-Campuzano E (2015) La complejidad del manejo de zonas de turismo  
1283 (eco) arqueológico en ciudades. El caso de Cuicuilco, México. *Pasos, Revista de*  
1284 *turismo y patrimonio cultural*. 13 (5):1079-1094.  
1285 <https://doi.org/10.25145/j.pasos.2015.13.074>
- 1286 Pérez-Méndez A (2007) *Las casas del Pedregal*. Editorial Gustavo Gili, Mexico City, 323 p
- 1287 Peterson FL (1972) Water development on tropic Volcanic Islands—Type example: Hawaii  
1288 a. *Groundw* 10(5):18-23
- 1289 Petrosino P, Iavarone R, Alberico I (2019) Enhancing Social Resilience Through Fruition of  
1290 Geological Heritage in the Vesuvio National Park. *Geoheritage* 11:2005–2024.  
1291 <https://doi.org/10.1007/s12371-019-00404-y>

- 1292 Pezzoli K (2000) Human settlements and planning for ecological sustainability: the case of  
1293 Mexico City. MIT press
- 1294 Pica A, Vergari F, Fredi P, Del Monte M (2016) The aeterna urbs geomorphological heritage  
1295 (Rome, Italy). *Geoheritage* 8(1):31-42
- 1296 Pica A, Luberti GM, Vergari F, Fredi P, Del Monte M (2017) Contribution for an urban  
1297 geomorphoheritage assessment method: proposal from three geomorphosites in Rome  
1298 (Italy). *Quaestiones Geographicae* 36(3):21-36
- 1299 Porta J, Poch, RM, López-Acevedo, M (2019) Edafología: uso y protección de suelos. 4<sup>a</sup>  
1300 Edición. Ediciones Mundi-Prensa, 603 p
- 1301 Portal C, Kerguillec R (2018) The shape of a city: Geomorphological landscapes, abiotic  
1302 urban environment, and geoheritage in the western world: the example of parks and  
1303 gardens. *Geoheritage* 10(1):67-78
- 1304 Reverchon F, Ortega-Larrocea MDP, Pérez-Moreno J, Peña-Ramírez VM, Siebe C (2010)  
1305 Changes in community structure of ectomycorrhizal fungi associated with *Pinus*  
1306 *montezumae* across a volcanic soil chronosequence at Sierra Chichinautzin, Mexico.  
1307 *Can J Forest Res* 40(6):1165-1174.
- 1308 Reynard E, Pica A, Coratza P (2017) Urban geomorphological heritage. An overview.  
1309 *Quaestiones Geographicae* 36(3):7–20. doi: 10.1515/quageo–2017–0022
- 1310 Rivera D (1945) Requisitos para la organización del pedregal. Accessed from a link on the  
1311 Wikipedia webpage titled « Jardines del Pedregal ».
- 1312 Rodrigues ML, Machado CR., Freire E (2011) Geotourism routes in urban areas: a  
1313 preliminary approach to the Lisbon geoheritage survey. *GeoJ Tour Geosites* 8(2):281-  
1314 294

- 1315 Rzedowski J (1954) Vegetación del Pedregal de San Ángel (Distrito Federal, México).  
1316 Anales Escuela Nacional Ciencias Biológicas, Instituto Politécnico Nacional 8:59-129
- 1317 Salas Portugal A (2006) Morada de lava. Universidad Nacional Autónoma de Mexico,  
1318 Mexico City, 204 p
- 1319 Sanders WT, Parsons JR, Santley RS (1979) The Basin of Mexico: Ecological Processes in  
1320 the Evolution of a Civilization. Academic Press, New York, 561 p
- 1321 Schmitter E (1953) Investigación petrológica en las lavas del pedregal de San Angel.  
1322 Congreso Científico Mexicano, Memorias 3 :218-237
- 1323 Schteingart M (1989) The environmental problems associated with urban development in  
1324 Mexico City. Environ Urbanization 1(1):40-50
- 1325 Self S, Keszthelyi L, Thordarson T (1998). The importance of pāhoehoe. Annual Review of  
1326 Earth and Planetary Sciences 26(1): 81-110
- 1327 SEREPSA (Secretaría Ejecutiva de la Reserva Ecológica El Pedregal de San Ángel) (2008)  
1328 Manual de Procedimientos. Programa de Adopción de la Reserva Ecológica del  
1329 Pedregal de San Ángel. Secretaría Ejecutiva REPSA, Coordinación de la Investigación  
1330 Científica, Universidad Nacional Autónoma de Mexico, Mexico City, 108 p
- 1331 Siebe C (2000) Age and archaeological implications of Xitle volcano, southwestern Basin of  
1332 Mexico-City. J Volcanol Geotherm Res 104(1-4):45-64. doi: 10.1016/S0377-  
1333 0273(00)00199-2
- 1334 Siebe C, Rodríguez-Lara V, Schaaf P, Abrams M (2004) Radiocarbon ages of Holocene  
1335 Pelado, Guespalapa, and Chichinautzin scoria cones, south of Mexico City:  
1336 implications for archaeology and future hazards. Bull Volcanol 66(3):203-225
- 1337 Siebe C, Arana-Salinas L, Abrams M (2005) Geology and radiocarbon ages of Tlálóc,  
1338 Tlacotenco, Cuauhtzin, Hijo del Cuauhtzin, Teuhtli, and Ocusacayo monogenetic

1339 volcanoes in the central part of the Sierra del Chichinautzin, México. *J Volcanol*  
1340 *Geotherm Res* 141:225-243. doi: 10.1016/j.jvolgeores.2004.10.009

1341 Siebe C, Mendoza-Hernández PE, Juárez-Orozco S, Vázquez-Selem L, Cram-Heydrich S  
1342 (2016) Consecuencias de la actividad volcánica del Xitle y el disturbio antrópico sobre  
1343 las propiedades del suelo y la diversidad vegetal del Parque Ecológico de la Ciudad de  
1344 México en el Ajusco medio. In: Comisión Nacional para el Conocimiento y Uso de la  
1345 Biodiversidad (conabio) y Secretaría del Medio Ambiente del Distrito Federal  
1346 (sedema). *La biodiversidad en la Ciudad de México*. Conabio/Sedema, Mexico City

1347 Siebe C, Macías JL (2006) Volcanic hazards in the Mexico City metropolitan area from  
1348 eruptions at Popocatépetl, Nevado de Toluca, and Jocotitlán stratovolcanoes and  
1349 monogenetic scoria cones in the Sierra Chichinautzin Volcanic Field. *Special Papers-*  
1350 *Geol Soc Am* 402:253

1351 Siebe C, Rodríguez-Lara V, Schaaf P, Abrams M (2004) Radiocarbon ages of Holocene  
1352 Pelado, Guespalapa, and Chichinautzin scoria cones, south of Mexico City:  
1353 implications for archeology and future hazards. *Bull Volcanol* 66:203-225.  
1354 doi:10.1007/s00445-003-0304-z

1355 Singh SK, Reinoso E, Arroyo D, Ordaz M, Cruz-Atienza V, Pérez-Campos X, et al (2018)  
1356 Deadly intraslab Mexico earthquake of 19 September 2017 (M w 7.1): Ground motion  
1357 and damage pattern in Mexico City. *Seismological Research Letters* 89(6):2193-2203

1358 Solleiro-Rebolledo E, Straubinger M, Terhorst B, Sedov S, Ibarra G, Sánchez-Alaniz JI,  
1359 Marmolejo E (2016) Paleosols beneath a lava flow in the southern basin of Mexico:  
1360 The effect of heat on the paleopedological record. *Catena* 137:622-634

1361 Straub SM, LaGatta AB, Martin-Del Pozzo AL, Langmuir CH (2008) Evidence from high-  
1362 Ni olivines for a hybridized peridotite/pyroxenite source for orogenic andesites from  
1363 the central Mexican Volcanic Belt. *Geochemistry Geophysics Geosystems* 9(3):1-33

1364 Ticar J, Komac B, Zorn M, Ferik M, Hrvatin M (2017) From urban geodiversity to  
1365 geoheritage: the case of Ljubljana (Slovenia). *Quaestiones Geographicae* 36(3):37-50

1366 Urrutia-Fucugauchi J, Goguitchaichvili A, Pérez-Cruz L, Morales J (2016) Archaeomagnetic  
1367 dating of the eruption of Xitle Volcano, Basin of Mexico: Implications for the  
1368 mesoamerican centers of Cuicuilco and Teotihuacan. *Arqueología Iberoamericana*  
1369 30:23-29

1370 Van den Berg AE, Maas J, Verheij RA, Groenewegen PP (2010) Green space as a buffer  
1371 between stressful life events and health. *Social Science & Medicine* 70(8):1203-1210

1372 Vereb V, van Wyk de Vries B, Guilbaud MN, Karatson D (2020) The urban geoheritage of  
1373 Clermont-Ferrand : from inventory to management. *Quaestiones Geographicae*, vol.  
1374 39(3):5-31; doi: 10.2478/quageo-2020-0020

1375 Waitz P, Wittich E (1910) Tubos de explosión en el Pedregal de San Angel. *Boletín de la*  
1376 *Sociedad Geológica Mexicana* 7:169-186

1377 Walker GPL (1993) *Basaltic-volcano systems*: Geological Society, London, Special  
1378 Publications 76(1):3-38

1379 Walker GPL (2009) The endogenous growth of pahoehoe lava lobes and morphology of lava-  
1380 rise edges. In : Thordarson T et al (Eds) *Studies in Volcanology: The Legacy of George*  
1381 *Walker*, Spec Publ IAVCEI 2:17-32

1382 Wittich E (1919) Los fenómenos microvolcánicos en el pedregal de San Ángel: *Memorias*  
1383 *de la Sociedad Científica Antonio Alzate*. México 38:101-120

1384 Wood CA (1980) Morphometric analysis of cinder cone degradation. *Journal of Volcanology*  
1385 and *Geothermal Research* 8(2-4):137-160

1386 WRB IUSS Working Group (2015) Base referencial mundial del recurso suelo 2014,  
1387 Actualización 2015. Sistema internacional de clasificación de suelos. Informes sobre  
1388 recursos mundiales de suelos 106. Food and Agriculture Organization of the United  
1389 Nations, Roma

1390 Zambrano L, Cano-Santana Z, Wegier A, Arroyo-Lambaer D, Zúñiga-Vega JJ, Suárez A, et  
1391 al (2019) Evaluating socio-ecological interactions for the management of protected  
1392 urban green spaces. *Frontiers in Environmental Science* 7:144

1393 Zambrano L, Rodríguez Palacios S, Pérez Escobedo M, Gil-Alarcón G, Camarena P, Lot A  
1394 (2016) *La Reserva Ecológica del Pedregal de San Ángel: Atlas de Riesgos*. Mexico  
1395 City, Mexico. Universidad Nacional Autónoma de México, Mexico City

1396

