Special Section
Monogenetic volcanism, environment and society

Geofísica Internacional (2024) **63-4**: 1265 - 1281

Forgotten Landscapes on Lava Flows in France and Western Mexico

Antoine Dorison[1,2] and Yves Michelin[3]

Abstract

Monogenetic volcanism has generated blocky lava flows in many parts of the world. These rugged environments are generally considered unsuited for human settlement, and today are used almost exclusively for quarrying or timber harvesting where vegetation has developed. Furthermore, the difficulty of access limits effective exploration by scientists. Nevertheless, several archaeological sites have been discovered on some of these flows, notably in Mexico. The recent development of remote sensing by airborne laser scanning (LiDAR) offers exceptional prospects for the study of these geological formations and their exploitation by humans. In this paper we compare two contemporary archaeological areas on Quaternary monogenetic blocky lava flows: the Zacapu area in western-central Mexico, and the Chaîne des Puys in Central France. Both areas have benefited from LiDAR coverage. Originally developed in the Mexican context, a remote sensing methodology based on digital elevation model processing and visualization was used to identify geoforms and anthropogenic features in both areas. Although separated by several thousands of kilometers, we show that the methodology is as relevant in France as it is in Mexico. Furthermore, we identified the recurrence of morphologies and associated types of archaeological site locations and patterns. We argue that this type of lava flow, though marginalized today, was attractive to human groups in ancient times as a strategic, but also a resourceful geoecological setting.

Key words: Michoacán-Guanajuato Volcanic Field, Chaîne des Puys, Archaeology, LiDAR, abandoned villages, landscape heritage.

Resumen

El vulcanismo monogenético ha generado coladas de lava en bloques en muchas partes del mundo. En general, estos entornos escarpados se consideran inadecuados para los asentamientos humanos y actualmente se utilizan casi exclusivamente para la explotación de canteras o la tala de madera, cuando están cubiertos de vegetación. Además, la dificultad de su acceso limita la exploración efectiva por parte de los científicos. No obstante, se conocen numerosos sitios arqueológicos en algunos de estos flujos, sobre todo en México. El reciente desarrollo de la teledetección mediante escáner láser aerotransportado (LiDAR) ofrece perspectivas excepcionales para el estudio de estas formaciones geológicas y de su explotación por los seres humanos. En este artículo comparamos dos zonas arqueológicas contemporáneas establecidas sobre coladas de lava en bloques resultantes del vulcanismo monogenético del Cuaternario: la zona de Zacapu, en el centro-oeste de México, y la Chaîne des Puys, en el centro de Francia. Ambas zonas cuentan con una cobertura por LiDAR. Se utilizó una metodología de teledetección desarrollada originalmente en el contexto mexicano que se basa en el procesamiento y la visualización de modelos digitales de elevación para identificar las particularidades de las geoformas y los elementos antropogénicos en ambas zonas. Aunque separadas por varios miles de kilómetros, demostramos que la metodología es tan pertinente en Francia como en México. Además, identificamos la recurrencia de morfologías antrópicas, así como de la distribución y del patrón de asentamiento arqueológicos. Argumentamos que los flujos de lava en bloques, aunque marginados en la actualidad, resultaban atractivos para los grupos humanos en la antigüedad como contextos geoecológicos estratégicos, pero también para la explotación de sus recursos.

Palabras clave: Campo Volcanico Michoacan-Guanajuato, Chaîne des Puys, Arqueologia, LiDAR; pueblos abandonados, patrimonio paisajistico.

Received: December 26, 2023; Accepted: June 10, 2024; Published on-line: October 1, 2024.

Editorial responsibility: Dra. Christina Siebe Grabach

* Corresponding author: Antoine Dorison, antoine.dorison@gmail.com
[1] CNRS, UMR8096 ArchAm Archaeology of the Americas, Paris, France
[2] CNRS, UMR7041 ArScAn team Environmental Archaeologies, Nanterre, France
[3] AgroParis Tech/INRAE/UCA/vetAgroSup, UMR 1273 Territoires, Clermont-Ferrand, France

Antoine Dorison, Yves Michelin.

https://doi.org/10.22201/igeof.2954436xe.2024.63.4.1772

1. Introduction

Monogenetic volcanism has produced blocky and scoriaceous A'a-type lava flows in many parts of the world. Although their structural morphologies (e.g., pressure ridges, levees) are smoothed over time by erosional processes and frequently by overlying ash layers issued by later eruptions, Quaternary flows are generally characterized by rugged surfaces. Steep slopes, rocky outcrops, and sporadic soil and plant cover constrain their exploitation by humans, and have generally led to the marginalization of these areas.

In Mexico, such processes are clearly evidenced by the name *malpaís* (bad land) that was given to this type of lava flow by the Spanish conquerors as early as the 16th century (Acuña, 1987: 104). Yet, archaeological sites on *malpaíses* are not uncommon (Piña Chan, 1975; García Cook, 2003; Michelet *et al.*, 2005; Pollard, 2008; Fisher & Leisz, 2013). The explanation favored by archaeologists to interpret this paradox is to consider these sites as defensive. However, a recent study based on a geoarchaeological approach combining remote sensing by airborne laser scanning (LiDAR) and fieldwork have shown that the appeal of these settings may also stem from their geomorphological and pedological characteristics (Dorison, 2019, 2022; Dorison & Siebe, 2023). The Mexican rugged lava flows turn out to be more varied than the indiscriminate use of the term *malpaís* would suggest. More broadly, *malpaíses* have not always been perceived in a negative manner (Dorison, 2022).

Thousands of kilometers away, in France, the A'a flows of the Chaîne des Puys, locally known as *cheires*, also show evidence of human occupation beyond their geoecological similarities with Mexican *malpaíses* (Michelin, 1996; Michelin *et al.*, 1996). The acquisition of LiDAR data in this area has recently led to an increase in the number of identifications of such traces, compelling us to reconsider the potential and perception of *cheires* over time.

In this article, we focus on two cases of human settlement on block-lava flows: the *Malpaís* de Zacapu volcanic cluster in northern Michoacán, Mexico, and the Chaîne des Puys in central France. In both cases, the flows studied spread over large surfaces. Locally, however, they are not the only alternative to human settlement. Numerous seemingly more suitable environments—such as Pleistocene volcanic plateaus with gentle relief and fertile soils—are available nearby. The question that arose, therefore, was to understand the motivation for settling on *cheires* and *malpaíses* during certain periods. In the history of research of these landscapes, LiDAR data offer for the first time a virtually exhaustive view of the complexity of visible anthropogenic features, and make it hence possible to address the settlement patterns with great accuracy. In order to better compare the French and Mexican contexts, we applied the same analytical methodology. First results show that the *malpaíses* and *cheires*, which are currently deprecated geoforms, were formerly attractive to human populations, for defensive as well as economic reasons. Based on these results, we finally discuss their value as an environmental and cultural heritage.

2. Contexts of the study

2.1. The Malpaís of Zacapu, Mexico

2.1.1 Environment

The *Malpaís* of Zacapu (MZC) is a 50 km² volcanic flow cluster located 300 km west of Mexico City, in the state of Michoacán (Reyes-Guzmán *et al.* 2018) (Figure 1). It lies within the Michoacán-Guanajuato Volcanic Field (Hasenaka & Carmichael 1985) in the Transmexican Volcanic Belt (Ferrari *et al.* 2012). It consists of nine partially overlapping lava flows dating from the Late Pleistocene (100,000 BP) to the Late Holocene (ca. 900 CE for the most recent; Mahgoub *et al.* 2017), at the western margin of the Zacapu lake basin, which was drained in 1900 (Arnauld *et al.* 1993). The basin is the result of regional tectono-volcanic activity that began in the Miocene. It generated a landscape of lava flows, cones, domes, and shields, whose lithology is chiefly intermediate in composition (andesites, basaltic andesites, dacites) (Reyes-Guzmán *et al.* 2018) (Figure 2). The climate is sub-tropical with a rainy season (monsoon) from May to October (800 mm) (García 2004). The average altitude of ca. 2000 m induces a marked day/night thermal amplitude, leading to frosts in winter. Under these conditions, the soils mainly result from the weathering of tephra deposits from successive eruptions (DETENAL 1979; Dorison *et al.* 2022). There is a marked contrast between the lowlands, influenced by almost constant wet conditions (Phaeozems, Histosols, Stagnosols, Vertisols), and the drier volcanic uplands with permeable geological substrates (Phaeozems, Andosols, Cambisols, Luvisols, Vertisols). Current agriculture is extensive and irrigated in the lacustrine plain, whereas it is seasonal and more fragmented in the uplands, where it alternates with scattered oak forest on rocky lava flows and grazing areas (Gougeon 1991; Labat 1995). Today, the *malpaíses* only serve as occasional wood and pasture reserves.

2.1.2. Prehispanic archaeology

Evidence of clearing around the basin are visible as early as the 2nd millennium BCE (Pétrequin 1994), but the first perennial settlements only appeared near the beginning of the common era, on islets on the western margin of the lake (Arnauld *et al.* 1993). The MZC was colonized from the 5th century onwards (Pereira *et al.* 2023), with a first demographic peak around the 8th

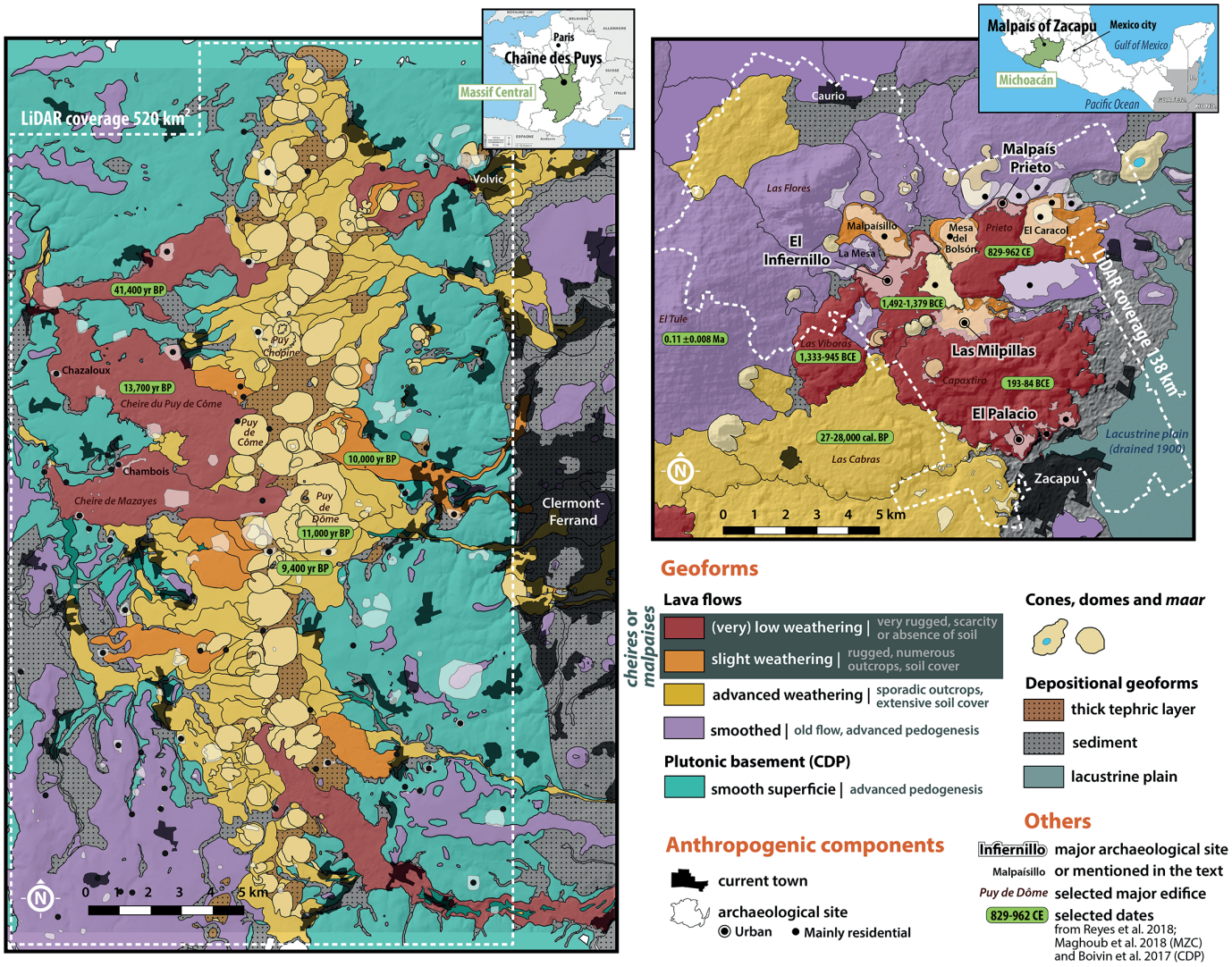

Figure 1. Simplified geomorphological and archaeological maps of the CDP (left) and the MZC (right) © authors based on data by Boivin *et al.* (2017) and Reyes-Guzmán *et al.* (2018).

century, followed by a hiatus in the occupation between 900 and 1250 (Dorison and Siebe 2023), probably linked to the eruption of the *Malpaís* Prieto volcano (Mahgoub *et al.* 2017). In the mid-13th century, the MZC was recolonized by allochthonous populations merging with smaller local groups, who built four urban centres, leading to a regional demographic climax (Michelet *et al.* 2005; Forest 2023; Dorison and Siebe 2023). The area was abruptly abandoned around 1450, with only diminished occupations remaining to the south of the MZC (Forest 2020). The effects of the Spanish colonization can be seen as early as in the 1530s, with the creation of a lakeside village to the east of the MZC (Lefebvre *et al.* 2023).

In the MZC, the remains visible on the datasets considered in this article are the stone foundations of houses and associated levelling works, civic-ceremonial features (pyramids and plazas), agricultural features, such as terraces and walls, as well as elements of a few ancient pathways (Dorison 2020). Agricultural activities of these prehispanic populations were strictly manual, with no draught animals or cattle, and animal domestication limited to turkeys, dogs, and bees (Rojas 1988). As a result, animal management facilities were minor.

2.2. The Chaîne des Puys, France

2.2.1. Environment

In the heart of the Massif Central, to the west of Clermont-Ferrand, the Chaîne de Puys (CDP) includes more than 80 volcanoes. Their lava flows are over 30 km long and 4 to 6 km wide, parallel to the N-S-oriented Limagne fault (Figure 1). Volcanism was active here between 95,000 and 8,600 BP (Boivin *et al.* 2017) and is part of the last phase of continental

rifting that gave rise to the Limagne Plain graben (Maccaferi *et al.* 2014). The latter resulted from a consecutive intra-plate stretching related to the Alpine orogeny in the Oligocene (35-25 Ma), after the fracturing of the leveled Hercynian massif. Miocene volcanic activity (23-12 Ma) led to the uplift of the Plateau des Dômes to the west of the area (Michon & Merle 2001). The CDP is a unique ensemble of monogenic volcanoes (cones, domes, maars) associated with trachyandesitic, trachybasaltic, and basaltic block-lava flows of varying lengths (Figure 2). This diversity is thought to have resulted from the stagnation of primitive magmas at depth and their subsequent differentiation towards more evolved compositions, from which mixtures and fractional crystallization processes arose (Martel *et al.* 2013). Among the block-lava flows locally known as *cheires*, geologists distinguish A'a-type scoriaceous flows from boulder lavas (Boivin *et al.* 2017). Formed 44,000 to 13,000 years ago, they are often partially covered by contemporary or later tephra layers and end with a steep ledge that dominates the plateau below by a few dozen meters. Their altitudes range from 1,000 m at the base of the cones to 650-700 m in the valley bottoms.

Over these 100,000 years of activity, the climate fluctuated greatly. The first eruptions took place at the beginning of the Würm 1 period, in a dry and cold, but not icy climate. During the Last Glacial Maximum (c. 21,000 years BP), the glaciers stopped to the north and did not reach the area. The last eruptions date from the early Holocene (pre-Boreal), in a rapidly warming climate where rising temperatures were associated with increased precipitation and a notable change in vegetation (Vivent & Vernet 2001). The open steppe was gradually replaced by forest, with a succession of different species over the last ten millennia.

Current human activity on the volcanoes and flows is limited. Some areas are grazed by sheep and cattle, maintaining a semi-natural vegetation of lawns and heaths. The remainder is covered by either natural deciduous, reforested (coniferous) or mixed forests. As climatic conditions have never been too extreme, and traditional human activity not very intense, the volcanic forms have changed little since their formation and retain a youthful appearance. This has helped to justify the inclusion of the CDP-Limagne fault region in the UNESCO World Heritage catalogue, with the exception of a few quarries whose activity is set to cease soon (PNR, classified site).

2.2.2. Pre-Modern archaeology

The area was probably populated as early as the last cold period. In the southern peat bogs, evidence of clearing is considered to represent the oldest trace of agriculture in the Massif Central (6000-6500 BP) (Miras *et al.*, 2004). The associated dwellings were temporary and in glades which, once exhausted, were abandoned and thereafter became spontaneously reforested again. Further land clearing followed during the Bronze Age (Michelin *et al.* 2001). Caches of this metal have been found without associated settlements. In the last few centuries BCE, the Arverne Gauls established an agricultural landscape. Several cities (*oppida*) appeared on the plain or on the edge of a fault near present-day Clermont-Ferrand (Ledger *et al.*, 2015), and the summit of the Puy de Dôme cone seems to have been worshipped.

After the Roman conquest, the plateau was rapidly colonized and developed. A capital (*Augustonemetum*) was created at the location of present Clermont-Ferrand, which was linked

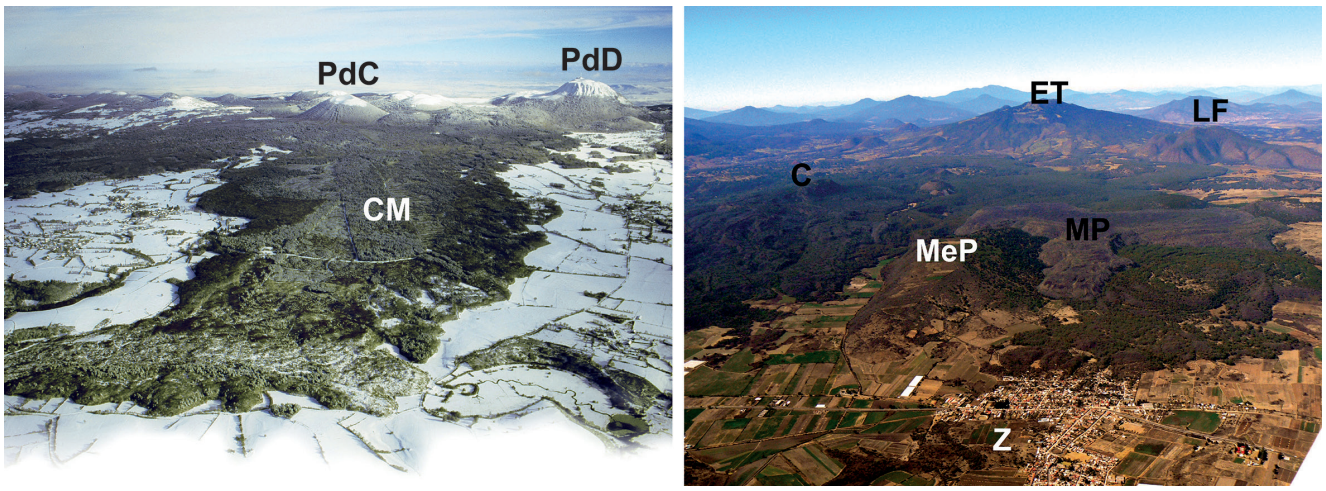

Figure 2. Aerial views from the west of the CDP (left, © M. Sagot) and from the east of the MZC (right, © C. Siebe). (PdC: Puy de Côme; PdD: Puy de Dôme; CM: Cheire de Mazayes; C: Capaxtiro; MeP: Mesa el Pinal; MP: *Malpaís* Prieto; ET: El Tule; LF: Las Flores)

by a Roman road to Saintes (south-western France), passing at the foot of the Puy de Dôme, where a shrine to Mercury was built. A temple dedicated to this god was erected on the summit using local trachytic rock (Boivin *et al.*, 2015). On the plateau, a *vicus* (town) is mentioned on the Peutinger table (*Ubrillum*), without precise location. Mining (gold, silver, lead) has also been identified. Economic activity was therefore significant during antiquity. However, with the exception of the Puy de Dôme and the trachytic cones (Puy Clersiou, petit Suchet) from which stone was extracted, archaeological traces are mainly found on the plateaus surrounding the CDP, where *villae* (estate) have been identified (Blanc *et al.*, 2013).

By the end of the Roman era, settlements were scattered. Forests had almost disappeared, giving way to crops and meadows on the plateau, and meadows and heaths on the rocky lava flows and volcanoes. The pollen diagrams show no signs of abandonment after the fall of the empire in the 5th century, suggesting that the landscapes remained open and dedicated to agriculture. Slight abandonment can be observed in the 9th or 10th century, following the regrouping of settlements around castles and churches, and then in the 14th century, during the Hundred Years' War. The forest then took over a large part of the *puys* and their lava flows, while the plateau remained in agricultural use (Michelin, 1996). From the 12th century onwards, texts are available and supplement the sedimentary archives that became disrupted by later human activities. They recount a deep reorganization of space, with the creation of seigneurial estates to the detriment of village collective lands, and a stronger hold by the lords over the communities (Charbonnier, 1980). Several sources mention seigneurial farming estates in the *puys*, and attempts to create parishes at high altitudes that are difficult to locate on the basis of toponymy alone (Comte *et* Grelois, 2005). This makes it particularly challenging to identify settlement evidence for the medieval period. Since much of the CDP is today forested and prospecting on the ground is laborious, the possibility of applying new technologies became a promising task.

The methodology was developed in four main stages: 1) LiDAR remote sensing data acquisition, 2) field verification, 3) laboratory work, and 4) data compilation.

2.3. LiDAR remote sensing, landscape archaeology, and GIS

In Mexico, LiDAR data were collected by the National Center for Airborne Laser Mapping (NCALM, Houston) in 2015 over an area of 92 km² as part of the ANR Mesomobile project (supported by the CNRS ArchAm Archaeology of the Americas laboratory) (Table 1). A second mission extended the coverage to 138 km² in 2021. In France, the Centre Régional Auvergne-Rhône-Alpes de l'Information Géographique (CRAIG) commissioned the companies GeoPhyt expert in 2011 and 2016, SETIS:IMAO in 2017 and 2018 and APEI-AVINEON in 2021 to cover a total of 520 km². The point clouds were used to construct comparable DEMs with a resolution of 0.5 m. The DEMs were processed with the Relief Visualization Toolbox (RVT) software (Kokalj & Somrak 2019) to generate the following visualizations: multiple hill-shading (MHS), slopes (S), sky view factor (SVF), simple

Table 1. Characteristics of the LiDAR equipment used (AGL: above ground level; PRF: pulse repetition frequency; NC: Not communicated)

Area	Funding organisation	Data collection agency	LiDAR equipment	Aircraft	Mean altitude AGL	Average PRF (kHz)	Scan angle	Scan freq. (Hz)	Average ground returns/ m²	Average DEM raster resolution (m)
MZC, Mexico	ANR Mesomobile project (CNRS ArchAm) 2015, 2021	NCALM	Teledyne Optech Titan MW multispectral lidar	Piper Chieftain (PA-31-350)	700 m 900 m 1,100 m	125×3 250×3 100×3	20°	20	12.2	0.5
CDP, France	CRAIG 2011	Geophyt expert	Leica AL70	NC	NC	-	NC	NC	NC	0.5
	April 2016				1000		50°	NC	10,6	0.5
	April 2017	SETIS/ IMAO	IGI Lite Mapper 6800	NC	600	-	60°	NC	10	0.5
	April 2018	SETIS/ IMAO	IGI Lite Mapper 7800	NC	850	-	60°	NC	10	0.5
	February-April 2021	APEI / Avineon	Leica City MapperII	NC	1500	-	40°	NC	NC	0.5

local relief model (SLRM) (10 and 50 px radii). Remote sensing was based on a combination of visualizations following the protocol originally established for Mexico (Dorison *et al.* 2022) which superimposes SVF>SLRM10px>SLRM50px>MHS and, in parallel, relies on a colorimetric reclassification of slopes (Srec) (Figure 3).

To mitigate misinterpretation, LiDAR data were systematically compared with available satellite images and historical sources providing information on land uses (e.g. ancient maps). Few data of the latter type are available for the Mexican context. However, the marginalization of the MZC since colonial times limits the phenomena of superimpositions of recent developments on prehispanic features. On the French side, where land reorganizations have been more numerous since the Middle Ages, independent sources have existed since the end of the 17th century (e.g. seigneurial *plans terriers*, Napoleonic cadastre). These documents were georeferenced using control points visible on ancient and current sources (e.g., building corners, road crossings, plot boundaries) as well as on LiDAR visualizations.

To process these datasets, a GIS was set up for each zone using QGIS. The digitization of features detected on LiDAR consisted of polygon delineation of the archaeological site footprint based on agglomeration criteria, distances between structures and identification of "natural" geomorphological boundaries. Nevertheless, particularly in Mexico, the sometimes almost continuous distribution of remains in space raised doubts as to the relevance of these artificial limits. They remain theoretical when ground-truthing fail to clarify them. Intra-site elements were digitized in the form of lines and polygons, according to their nature. This last work is well advanced in Mexico and only just begun in France, and is still in progress.

2.4. Ground-truthing

In Mexico, several foot survey campaigns with systematic recording of features were carried out for several years and included digging of test-pits and semi-extensive excavations (Pereira *et al.* 2016, 2020a, 2023; Dorison 2019). In France, verifications have only just begun, and no post-LiDAR archaeological excavations have yet been carried out because of the long duration of administrative procedures. In both cases, foot surveys were conducted with direct geopositioning on the LiDAR images, first with a differential GPS (Mexico), then with tablets equipped with the Qfield application, which enables direct digitization of elements and daily synchronization with QGIS in the post-operational phase.

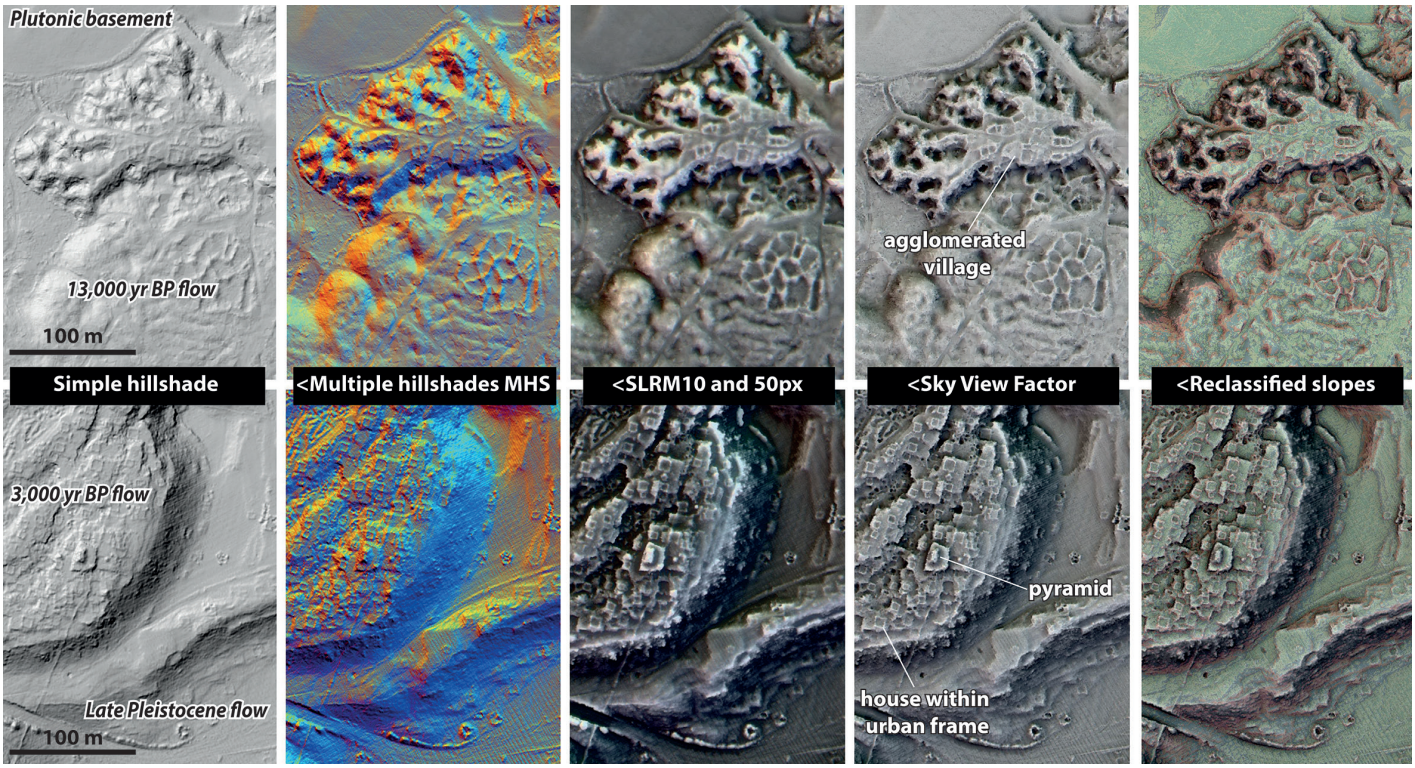

Figure 3. Examples of LiDAR visualization used in both case studies (up: CDP, "Les Roches" archaeological site; down: MZC, "Las Milpillas" archaeological site) © authors.

2.5. Spatial analysis, dating, and compilation

In both areas, a first level of analysis allowed us to identify and categorize sites across the entire LiDAR footprint (see below). On the Mexican side, several smaller areas have already been the subject of deeper studies, including feature-scale excavation and mapping (Pereira *et al.* 2016, 2020a, 2020b, 2023; Dorison 2019; Dorison & Siebe 2023; Lefebvre *et al.* 2023; Forest 2023), ceramic typochronology (Michelet 2013; Jadot 2016; Castañeda 2023), and radiocarbon dating (Michelet 1992; Pereira *et al.* 2020b). In France, following the identification of sites over the entire LiDAR coverage, a zoom was made on the young lava flows in the western part of the CDP, whose geomorphology is similar to that observed in the MZC. The analysis was restricted to the distribution of constructions (e.g., habitats, defensive structures) with regard to geomorphological and neighborhood criteria. It should be noticed that the non-volcanic plateau, on which the cones and associated lava flows rest, is essentially dedicated to livestock farming and is the area where most current villages are located. Thus, far fewer elements are visible on the LiDAR images. Furthermore, the area has been the subject of important land consolidation during the 19th century, so that ancient traces have been partially erased and the ancient parcel systems visible on the LiDAR images often coincide with those of the Napoleonic cadaster (this intricate point is not developed further in this article). Preliminary dating of the features identified in the lava flows of the CDP is based primarily on site-morphology. A small part of the corpus is mentioned in ancient texts and sporadic excavations document certain settlements (Tournadre, 2017, Fournier *et* Grelois, 2023).

Finally, it should be stated that the interpretation of the environmental contexts of the sites is based on existing documentation, particularly cartography (Reyes-Guzmán *et al.* 2018, 2021; DETENAL 1979; Dorison 2019; Dorison *et al.* 2022 for the MZC; Boivin *et al.* 2017 for the CDP).

3. Results

3.1. Archaeological site identification and typology

3.1.1. *Malpaís* of Zacapu

In the MZC, LiDAR revealed 46 new sites within the 138 km² covered, bringing the overall count in this window to 79. However, apart from the discovery of a large monumental complex (La Mesa), these new sites are generally small settlements that are difficult to access and under forest cover. The real breakthrough came with the discovery of the true extension of the sites already known, whose surface area turned out to be two to three times larger, than originally thought in most cases. In sum, 41 of the settlements are located on blocky *malpaís*-type lava flows. They account for over 70% of the 10,000+ features digitized to date. Fieldwork has enabled us to date these sites to the period between the 5th and 15th centuries CE. In a simplified typology, we can define five main categories (Figure 4).

1. Urban centers (4 [+14]). Built on malpaíses, these correspond to the four dense, agglomerated settlements already well documented. Spread over 50 to 100 ha each, they all contain 1,000+ houses. Largely residential, they also feature civic and ritual components (e.g., plazas and temples), as well as economic components in at least three of them (e.g., agriculture). Some are clearly defensive in character (e.g. rampart-like residential terraces). LiDAR has enabled us to enhance our understanding of their density, surface area and internal components, and to identify 14 reduced groups of features that are interpreted as satellite settlements.
2. Villages (31). These are residential settlements of more than 10 houses, built mainly on *malpaíses*. The settlement in them is scattered over several dozen hectares, punctuated by civic-ceremonial spaces and embedded in a dense agrarian frame (networks of terraces).
3. Isolated settlements (22). These are groups of a few houses, generally located in summit contexts, surrounded by agrarian features. They may display a more or less clear civic component, which makes it difficult sometimes to distinguish them from the next type.
4. Isolated civic-ceremonial areas (6). These are either monumental architectural groups at the top of reliefs, or isolated outcrops on which numerous rock art manifestations have been identified.
5. Economic activity areas (2). These are establishments essentially dedicated to a specific activity. The first is an open-pit and drift mine (Quezada *et al.* 2023). The second is a series of settlements on a blocky lava flow with a probable agrarian function (Dorison 2023a).

Ancient agricultural developments throughout the 138 km² were important. Thus, although the sites were essentially defined on the basis of the identification of residential or civic architecture, the almost continuous distribution of agrarian remains on all the geoforms with exploitable soils, both within and around the MZC lava flows, calls into question the representativeness of the "architecture" criterion for establishing site boundaries.

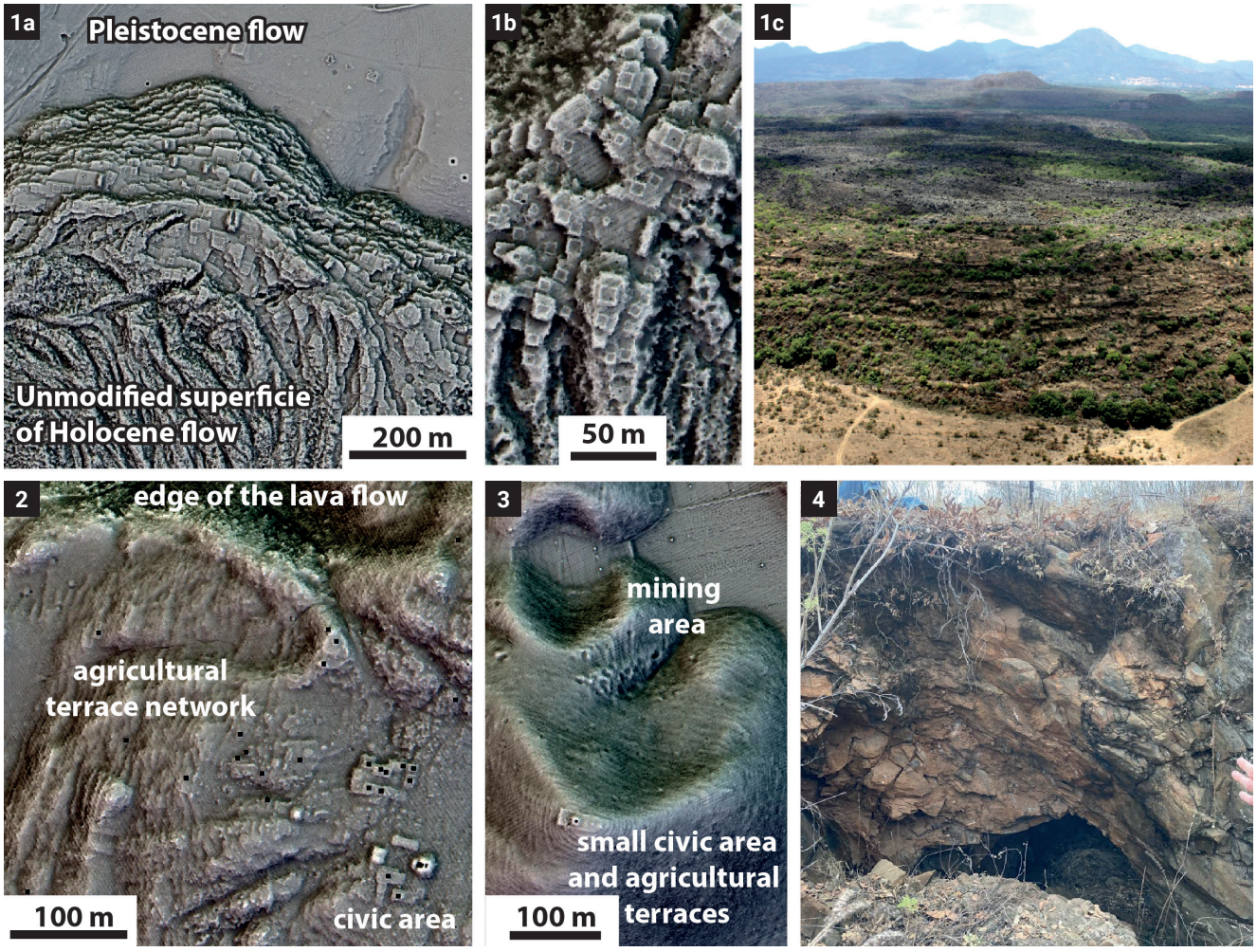

Figure 4. Examples of the types of site encountered in the MZC © authors (1a: city on lava front [*Malpaís* Prieto]; 1b: detail of urban grid in the same site; 1c: aerial view of the same site from the north [© G. Pereira]; 2: village on Pleistocene flow; 3: mining area and isolated civic area on cone summit; 4: field view of a mine).

3.1.2. Chaîne des *Puys*

In the CDP, within the 520 km² covered, 189 objects have been identified, of which 38 are still uncertain and five are of recent origin (19th-20th century mines and quarries). Within this corpus, 60 sites are located on blocky lava flows. Although age assignments remain tentative, most of the elements appear to date to the Middle Ages. The ground-truthing survey carried out so far has enabled us to group the objects detected into four main families (Figure 5).

1. Defensive sites (15). These present two contrasting aspects: rustic forms that are hard to detect and complex defensive systems, often already known before, such as *mottes castrales* or lime masonry architecture (e.g., Château de Chambois). The latter are probably more recent than the *mottes*, that were built from the beginning of the 11th century to the end of the 13th century (Gaime 2012), but the absence of archaeological excavations implies that this doubt cannot be resolved at this moment. Most have associated farmyard-type housing.
2. Villages and hamlets (25). These consist of roughly rectangular structures, either clustered together or separated by paths or streets. The dry-stone walls rarely exceed 2 m in height. Only the "Camp des Chazaloux" site has been excavated and dated to the period from the 13th century to the end of the 16th century (Fournier P.F., 1979; Tournadre, 2017). Three quarters of the area occupied by hamlets and defensive systems are under forest cover, confirming the value of LiDAR imagery for locating them.
3. Isolated buildings (16). These are mills, barns, or seigneurial agricultural estates. Most were already known from ancient sources. However, LiDAR has enabled us to pinpoint their location.

4. Tras (16). Corresponding to pastoral temporary habitats, they have a specific comb shape. They are well documented in the Massif du Sancy, some 30 km to the SW of the CDP (Fournier, 1983; Surmely *et* DeJunter, 2017). Following the first LIDAR mission in 2012, a field survey helped clarify their use.

3.2. Similarities at the feature scale

Trying to establish a typology common to both study areas based on LiDAR images, notably on the basis of domestic, civic, and ritual architecture, would be a laborious and probably irrelevant exercise. Bioclimatic conditions and multi-century cultural trajectories differ too widely, so that a comparison between a single-cell house from Western Mexico, where most domestic activities take place in an outdoor courtyard all year round, and a French medieval house or multi-storeyed fortification in a mountain climate where temperatures remain below zero for several months in winter, is of no real interest. However, there are a number of similarities, which raise questions as to why ancient societies settled in what are now considered hostile environments.

At the scale of the archaeological site and its internal components, these similarities are of an architectural nature or linked to the need to adapt to the terrain. The first point of comparison is the use of volcanic rocks for construction. While these are generally sourced *in situ*, there are works documenting quarries used to obtain certain rocks with selected properties for construction in France (Boivin *et al.* 2015) or for tool manufacturing in Mexico (Quezada *et al.* 2023). Although in France the use of mortar is attested on buildings as early as the 12th century (e.g., châteaux), the norm, as in Mexico, is dry stone construction (2b in Figure 5).

Moreover, the management of the ubiquitous volcanic rock is not limited to the construction of buildings. The second point of comparison is the identification of systematic removal and accumulation of outcropping blocks from the rugged surface of the flows to level and partition spaces. In Mexico, this strategy is expressed in the construction of stepped residential terraces on the flow fronts, creating levelled surfaces of tens to thousands of square meters (e.g., *Malpaís* Prieto, Las Milpillas, El Palacio) (1 in Figure 4). Similarly, volcanic rock was moved *in situ* to build imposing quadrangular platforms. Another material expression of these strategies in the MZC is the clearing of activity areas within the naturally planar areas of the flows (e.g., El Infiernillo, El *Malpaís*illo). As a result, these areas are demarcated by stone curbs that form more or less angular parcel morphologies. Recent works suggest a domestic function, but perhaps also an agricultural one (Dorison 2019: 557-562, 2023b; Siebe *et al.* 2023: 28-30).

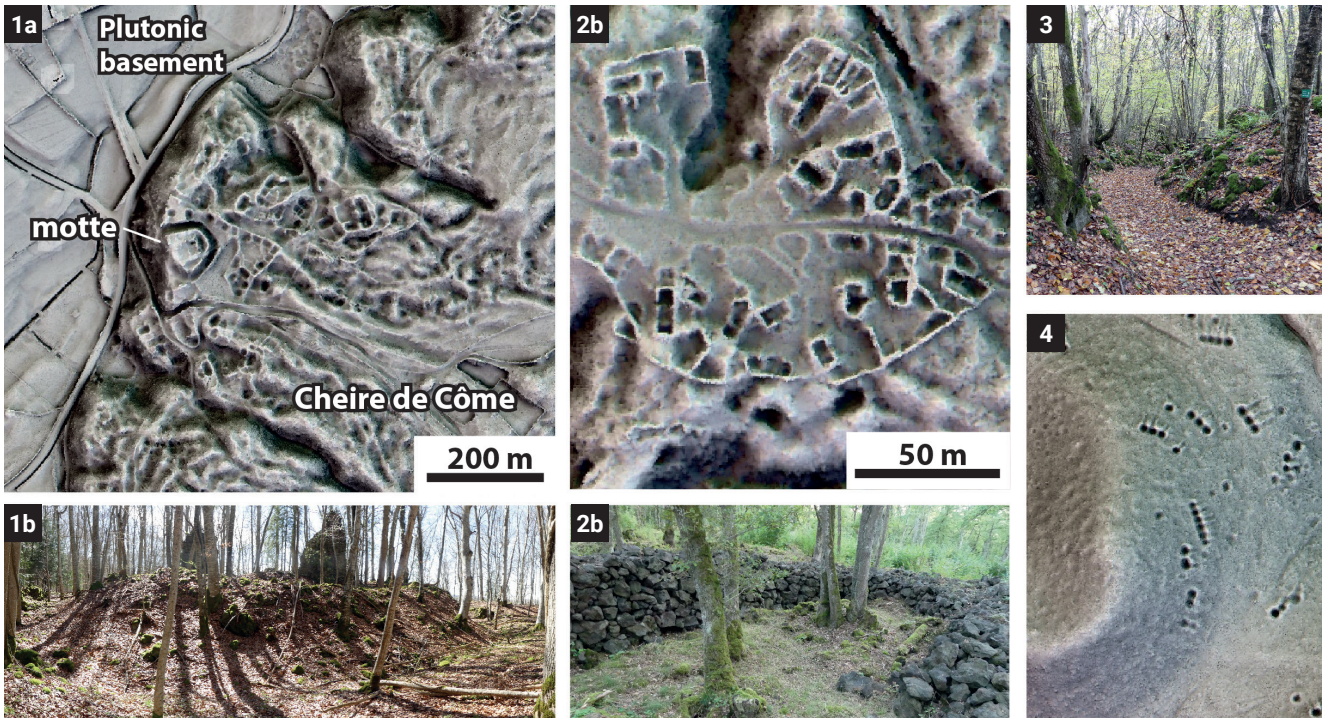

Figure 5. Examples of the types of sites encountered in the CDP © authors (1a: defensive site with associated village [Chambois]; 1b: field view of the *motte*; 2a: fortified village [Chazaloux]; 2b: field view of one building inside the latter site; 3: pathway within lava flow; 4: *tras* on cone).

While residential terraces on lava flow fronts are virtually absent in the CDP, enclosures and plots demarcated by dry-stone walls in connection with the habitat have been detected and likely respond to similar construction modes (by removal and accumulation). In addition, LiDAR enabled us to locate numerous well-developed traffic routes (rough pavements, stonework) (3 in Figure 5) with locally linear excavations corresponding to the repeated passage of carriage wheels. The same strategy was applied to the construction of numerous buildings in very rugged rocky areas. If we compare these constructions with the natural appearance of the lava flow in the continuity of the settlements, the LiDAR image clearly highlights these significant but discreet levelling efforts as they follow the morphological shapes.

More generally, in Mexico as in France, the sites identified are adapted to the specific features of the irregular volcanic surface. Enclosed areas occupy micro-depressions. Pathways follow lava pressure-ridges. However, when the surface is too irregular and obstacles cannot be avoided, localized anthropogenic works are clearly visible on the LiDARs (e.g., pitting of holes, incision of ridges, levelling of slopes). Furthermore, similarities are also noticeable at larger scales.

3.3. Site integration in the environment and exploitation of the latter

A feature common to both of the studied contexts is the relative altitude above surrounding ground of the blocky flow sites. From their position the view dominates the surrounding plains and plateaus. Similarly, there is a tendency to settle on flow fronts. This can be explained by the progressive mode of colonization of these areas and the defensive character that such a position provides, as discussed below. The *Malpaís* Prieto and El Palacio sites in Mexico, for example, are strictly confined to the front of two particularly rugged flows dated to the Late Holocene, dominating respectively a plateau to the north and the lacustrine plain to the southeast. A similar situation can be observed in France, where the Château de Chambois and the Camp des Chazaloux are both built at the front of a lava flow dominating the plateau to the west.

However, whereas in France residential areas remain restricted to the edges of the lava flow, in the MZC housing architectures often extend much further into the lava flows. This inward advance requires a certain degree of sediment formation, as at the Malpaisillo, Caracol, and Mesa del Bolsón lava flows, which are entirely covered by settled areas. The El Infiernillo flow is the most extreme case, since the prehispanic remains extend far out onto a very rugged lava plateau, which displays very little soil cover and important efforts to level and clear the flow's surface. In France, numerous constructional elements other than houses were found within the interior areas of flows, which are significantly more covered by sediments than their Mexican counterparts. Their function remains enigmatic in some cases, but the morphologies suggest grazing areas, woodlands, quarries, or cultivated plots.

Concerning the economic exploitation of the lava flows, the comparison with the Mexican examples is of particular interest. In fact, the settlement sites on the sediment-covered parts of the irregular blocky flows of the MZC host a significant agricultural component. There, numerous terraces and cultivated plots were built around the houses. A more detailed analysis has shown that houses were generally built in those parts of the flows that are particularly rugged (e.g., pressure ridges), to avoid and leave free the flatter sedimented smoother areas that could be cultivated (Dorison 2019, 2022; Pereira *et al.* 2023). In the irregular lava flows of the CDP, the cleared areas and identified plots could reflect a similar strategy. Housing would be limited to the edges of the lava flows, but their interiors could be devoted to different economic activities. This hypothesis is reinforced by the identification of occasional terraces blocking natural flow zones (e.g., between pressure ridges). This type of terrace, known as cross-channel terraces in various geomorphic settings, is common throughout Mesoamerica and numerous examples can be found in the MZC.

Finally, the communication routes within and between sites should be addressed. The existence of roads in the villages of the CDP have already been mentioned. More widely, LiDAR-based remote sensing has allowed to detect numerous paths, often demarcated by low walls and access systems (e.g., ramp paths). They link the sites of the flow fronts to each other, to the plateau, or to economic sectors within the *cheires*. In Mexico, apart from a few exceptional cases such as the pathways at the El Infiernillo site, which take forms that are similar to those observed in the CDP, or the access and staircase systems identified at various sites, these communication networks are less extended and not readily apparent.

4. Discussion

This comparative approach highlights a number of similarities between the occupation of rugged young lava flows in the MZC and in the CDP, despite their geographical and cultural distance. The abundant use of local rocks for dry-stone construction and tool-making, the strategies of removal and accumulation to level, clear, and delimit spaces, the settlement on flow fronts in topographically dominant positions, and the colonization of the lava flow interiors for economic reasons are all examples of these similarities. On a broader level, it is interesting to note that

the sites on *malpaíses* and *cheires* briefly presented here do not correspond solely to areas devoted to specific activities. Many are villages, or even towns, that concentrate the variety of domestic, civic and ritual activities inherent in what we should call living spaces. This observation calls into question the value given to, and the perception of, these rugged lava flow landscapes several hundred years ago in France and Mexico.

4.1. Defensive hypothesis

In Mexico, archaeologists traditionally explain the presence of settlements on the austere *malpaíses* as a necessity for defense. It is true that many of these settlements appear to have been created around the year 1000, at a time of heightened tension between groups, as seen by the emergence of warrior castes at the top of the social pyramid (Hers 1989; Healan & Cobean 2012) and, in some cases, evidence of increased physical violence (e.g., Pereira 2007). In France, the discovery of *cheire* sites is relatively recent. As a result, few hypotheses as to their origin and purpose have yet been proposed. However, the defensive hypothesis is the first that comes to mind, particularly for the few sites known from the 19th century (Contejean, 1864).

In France, given the distribution of newly identified residential settlements, the protective character of rugged flows, appears obvious and relevant. The sites are in a dominant position, exclusively on the fronts of the lava flows, often featuring clearly defensive structures, such as fortifications (Figure 6). Their field of vision is excellent, both between themselves and over the surrounding environment. To validate this hypothesis, and focusing on the three lava flows in the western part of the CDP where we identified five defensive and seven residential sites, we located the features most closely resembling defensive structures (*motte*, tower, *castrum*) and hypothesized that they may have included a wooden tower, as it was frequently the case in the 11th century (Bourgeois, 2013). For each point we defined a possible height (10 m for the *mottes* that could have had only wood towers, 15 m for the 2 cemented stone towers and 33 m for the highest tower of Pontgibaud castle). Then, we carried out a visibility analysis from each point. The result shows two complementary aspects: the very good visual coverage of both, the lava flow and the plateau, and the interconnection between defensive sites, enabling them to communicate with, or to surveil each other. In Mexico, this hypothesis might also be valid, since several settlements are similarly situated, and some also feature ostentatious defensive features. *Malpaís* Prieto is the best example, with its rampart-like terraces and excellent visibility over the plateau it dominates (Figure 6).

Nevertheless, there are a number of arguments that belie this over-simplistic explanation. If only in terms of visibility, we note that in Mexico, the major contemporary urban centers of the MZC have very limited visibility of each other (Dorison 2019: 610-611). Even more striking, the detailed study carried out in the MZC has shown that human colonization of the *malpaíses* began well before the year 1000 and the period of social unrest mentioned above (Dorison ibid.). Similarly, in the CDP, all settlement sites are associated with other developments, such as walled roads, quarries, and enclosed plots. Thus, the colonization of the interior of the sediment-covered parts of lava flows in both study areas clearly indicates motives that are different from purely defensive purposes.

4.2. Economic hypothesis

Indeed, in Mexico, despite certain taphonomic biases (e.g., destruction of structures in today's cultivated areas, greater sedimentation rate in the ancient lacustrine plain), the number of residential sites on lava flows in the MZC is high, reflecting a cultural choice by prehispanic populations to settle preferentially in these specific environments. The prehispanic pattern is thus almost opposed to colonial and present-day settlement predilec-

Figure 6. 3D views of archaeological sites on lava front (left: *Malpaís* Prieto city, MZC; right: Château de Chambois, CDP) © authors.

tions near the lake's shores. In France, although the situation is far from being clear, the evidence of economic development in the interior of the lava flows associated to housing sites at its margins, suggests that the appeal of the *cheires* was also not limited to their defensive character. This is further evidenced by the distribution of sites classified as essentially defensive (*motte* or castle), the majority of which occupy promontories on the plutonic plateau rather than on the *cheires*' edges.

The more intense colonization of the interior of the rugged lava flows in Mexico can perhaps be explained by the Mesoamerican technical and cultural background in the practice of agriculture. As already mentioned, prehispanic agriculture was manual, with no cattle or draught animals. Cultivating sediment-covered areas between outcrops of stony lava flows was therefore not a major constraint. Moreover, the soils of the MZC developed from parental tephras intermediate in composition (andesites, basaltic andesites), ensure high chemical fertility in addition to good physical properties. Previous work has shown that, from a prehispanic agricultural perspective, cultivating in and around the MZC was safer for crops than trying to drain the hydromorphic soils bordering the ancient lake (Dorison 2022).

Western agricultural know-how and traditions in the CDP differ widely. It would be reductive to attempt to apply the same model. Nevertheless, the archaeological traces revealed by LiDAR suggest the existence of rock quarries and agricultural plots. From the 12th century onwards, written documents (grazing contracts, deeds of sale) mention these activities in the *cheires*, and from the 17th century onwards, other sources such as lawsuits, land registry plans, and forestry administration archives confirm that the *cheires* were exploited and coveted territories where village communities and local lords clashed to control usage and income (Puy-de-Dome Department' Archives, AD63-16H142, 1642; AD63-2E931, 1748). Soil fertility is less homogeneous than in the MZC. The local pedology is complex, notably as a result of the alternation between episodes of mafic and sialic volcanic explosive eruptions in the history of the CDP (Boivin *et al.*, 1982). Nevertheless, the *cheires* soils are far from being devoid of agricultural potential, which was very probably exploited by the villages of the flow fronts when they were inhabited, and even by communities living on the nearby plateau.

Finally, quarries are important areas of economic activity in both study contexts, for the supply of specific building materials in the CDP and for lithic tools in the MZC.

Taken together, these elements indicate that lava flows played a much more important role in the economy of village communities at certain periods in history, in Mexico as in France. It is noteworthy that, despite the cultural and geographical distance, the period of greatest activity in these particular contexts seems to be between the 13th and 15th centuries CE. However, this observation needs to be put into perspective. In France, there are not enough reliable dates to build a solid argument on this point, while, in Mexico, recent works have shown that occupation of the rugged flows began well before this period. *Cheires* and *malpaíses* were an integral part of the socio-economic landscapes and settlement dynamics of the periods concerned, and were an essential component that regressed after the French Revolution in the CDP and after the Spanish colonization in Mexico.

4.3. A long-term view: rise and decline of anthropogenic features on rugged lava flows

These marked changes in the perception of rugged lava flows over time have significant repercussions on their evolution as landscapes. LiDAR imagery enables us to assess the distribution of their components on an unprecedented scale. While they reveal only part of the remains—those that have left traces on the surface—they also shed light on overlaps, superimpositions, and the partial or total destruction of older structures. In other words, they also give us direct information on the evolution of practices and perceptions. The forms detected and studied in this work were born of settlements in the *cheires* and *malpaíses*. They ceased with their abandonment, in the 15th century in Mexico and probably around the same time in France. Even though they are forgotten, they are still part of the environment, although they go unnoticed to the untrained eye. By many, they are considered as natural elements and also treated as such.

With the Spanish colonization, the Zacapu region experienced rapid marginalization of the *malpaíses*, which became arbitrarily divided by the walls of *haciendas* now lost in the middle of the woods. European-style farming conquered the shores, then drained the lake and became extensive. Today's farmers are confronted with frequent waterlogging in many areas and, by their own admission, often prefer the plateau soils around the MZC, which are less risky for crops, even though the complex ancient agricultural management of the *malpaíses* has been totally forgotten. In recent years, the privatization of common lands has led to the expropriation and forceful re-exploitation of the "natural" landscapes they constitute. With the help of larger investments and heavy machinery, avocado trees with deep roots are planted in fenced-in fields, while in other areas of the MZC trucks are driven onto the lava flows to be filled by cut oak trees (Figure 7).

In the CDP, several villages and their associated terroirs have also undergone profound changes since they were abandoned. For instance, the ancient village of l'Estrade, mentioned in texts up to the 15th century (Fournier *et* Grelois, 2023), disappeared from memory before the 18th century (Figure 8). The village and its land became a common grazing area, undivided between several villages. By the end of the 18th century, however, plans

Figure 7. Destruction on El Infiernillo archaeological site (left: view of a truck path and deforested area; right up: satellite image showing the deforested area; right down: LiDAR image showing the destroyed part of the prehispanic urban site). © First author

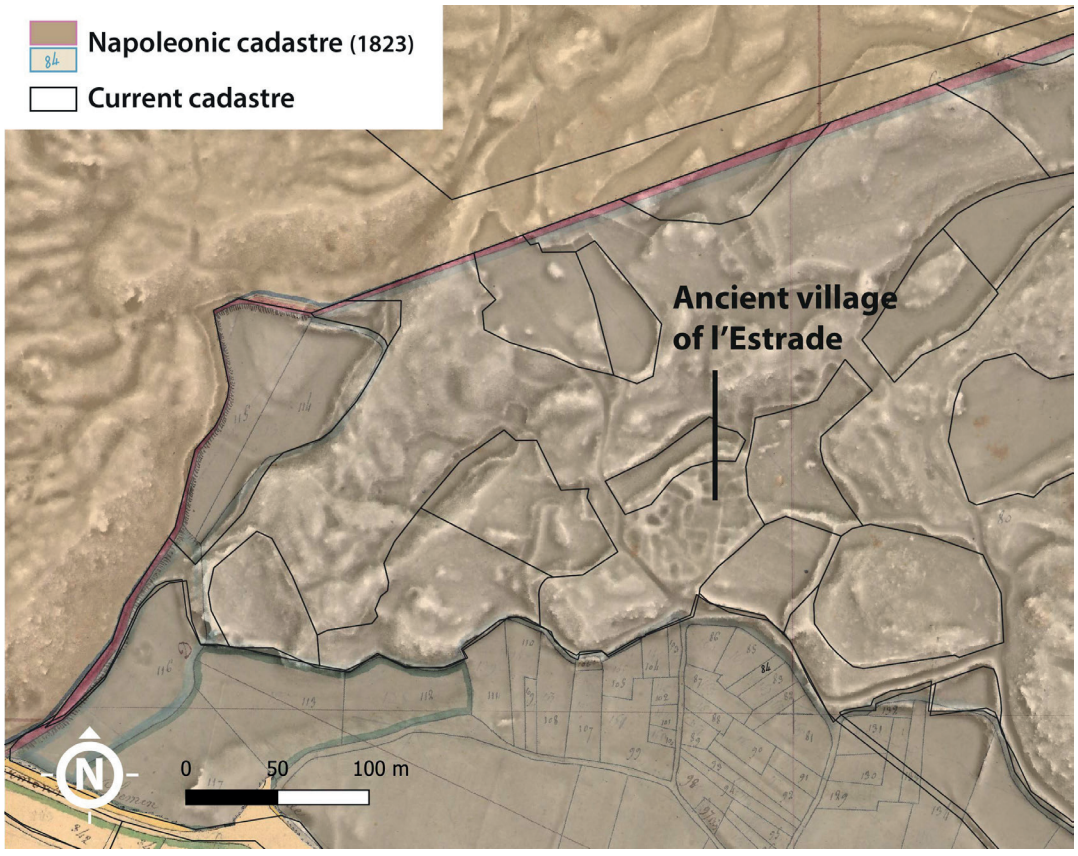

Figure 8. Evolution of the cadaster at l'Estrade archaeological site. The image shows that the village lies inside a single common property plot on the Napoleonic cadaster, whereas the latter has been fragmented and the village partially destroyed to create the current cadaster. © Author

and texts show the beginnings of individual appropriation, as also observable on LiDAR images. The part of an ancient parcel of land contemporary with the ancient village was probably reorganized in the early 19th century, as it no longer appears on the 1765 terrier map, and another parcel covering it is present on the 1822 Napoleonic cadaster. Other plots of land cut out part of the old village. They are not recorded in the Napoleonic cadaster, but are registered on the current one, which suggests a later appropriation. Another example is the detection of disrupted parcel systems and road networks that result from the vast forest replanting on *cheires* that took place between 1880 and 1930, and again between 1986 and 1988, this time with the support of heavy machinery, following the devastating 1982 storm.

Since 2018, the *cheires* have been part of the "Chaîne des Puys – Faille de Limagne" site, which is inscribed on the UNESCO World Heritage list as an "important tectonic area". This listing helps to protect them. In the minds of the managers, the idea was to promote the notion of a site whose natural aspect stemmed from pastoral and forestry management practices which, because they were based on local geomorphic specificities, maintained this natural aspect. However, as past and present human activities are virtually invisible to most visitors and even to many scientists, it is difficult to integrate traces of this past into management schemes. In this respect, all the discoveries made with LiDAR images are helping to raise awareness: although these areas may look natural, they are not pristine, but humanized areas, whose ecological richness is also the result of its history. This is not a unique phenomenon, as noticed by several authors in both America and Europe.

The rugged flow landscapes of the MZC and CDP are more complex than they appear. In addition to geoecological legacies, they also harbor cultural heritages. The two are inseparable. Today, this subtle balance is being called into question both by environmentalists, who reject all human activity in the name of protecting an idealized "nature", and by certain local or exogenous developers, who see these marginal areas only as a potential resource to be exploited, sometimes at catastrophic environmental and social costs. It is therefore necessary to consider new management methods, integrating their heritage value and the local people's needs. Documenting this history, both natural and human, and disseminating it, as we are attempting to do, is a first step.

5. Conclusion

Today, many people regard rugged flows resulting from monogenetic volcanism as an immutable environmental heritage, materializing the action of forces of nature, from which humans place themselves as observers (see Descola 2005). Apart from this vision, these areas, where rocky outcrops are omnipresent, are generally marginalized. In the CDP, their inclusion on UNESCO's World Heritage List gives them a certain degree of protection, and their tourist appeal integrates them into current economic dynamics, while at the same time freezing them into a perception that opposes nature and culture. In the MZC, non-compliance with regulations and land privatization policies makes these areas prone to abuse.

However, our modest comparative approach shows that archaeology and, in particular, the contribution of modern remote sensing techniques, reveal another facet of the history of these geoforms. It shows that ancient occupation of these flows was more widespread and more common than previously thought. The diversity of morphologies observed reflects a diversity of forms of exploitation and a difference in perception of these areas at certain times in history. Far from being depreciated, *cheires* and *malpaíses* constituted geoecological contexts that were not marginalized in past times, but fully integrated into local socio-economic and territorial dynamics.

Odds are that these observations are not limited to the Mexican and French examples documented in this study. In fact, this work raises the question of how to design new management strategies for this type of geological formations and, more broadly, for so-called "natural" areas. *Malpaíses* and *cheires* are not entirely natural areas. They have been intensively used by humans in the past, in the same way as other allegedly "natural" landscapes in France (see Ballut & Michelin 2014 for instance), in the Maya tropical forest, where the extension of archaeological sites has recently been revised upwards by LiDAR missions (Canuto *et al.* 2018), or even the "virgin" forest of Amazonia, once occupied by networks of prehispanic urban sites (Heckenberger 2020; Rostain *et al.* 2024). Current discoveries of hidden aspects of environments and the integration of humans into them, driven by technological advances such as LiDAR, invite us to reevaluate and reconceive our environmental heritage with both, its anthropic and natural dimensions, while considering the concrete needs of current local populations.

6. Referencias

Acuña, R. (1987). *Relaciones geográficas del siglo XVI: Michoacán.* Universidad Nacional Autónoma de México.

Arnauld, M.-C., Carot, P., & Fauvet-Berthelot, M.-F. (1993). *Arqueología de las Lomas en la cuenca lacustre de Zacapu, Michoacán, México.* Centre d'études mexicaines et centraméricaines.

Ballut, C., & Michelin, Y. (2014). Des zones humides pas si sauvages que cela: Apport des données historiques et paléo-environnementales à la réflexion sur la gestion des paysages de la chaîne des Puys

(France). *Développement Durable et Territoires*, 5(3). doi: **https://doi.org/10.4000/developpementdurable.10586**

Blanc, A., Dacko, M., Dousteyssier, B., Lamoine, L., Nectoux, E., *et al.* (2013). Les élites et les marqueurs du développement. En A. Frédéric Trément (Ed.), *Les Arvernes et leurs voisins du Massif Central à l'époque romaine. Une archéologie du développement des territoires* (pp. 11-29). Revue d'Auvergne.

Boivin, P, Langlois, E, Besson, J.C, Briot, D., Deniel, C., Gourgaud, A, Labazuy, P, de Larouzière, F.D., Livet, M, Meddard, E., Mercieca, C., Mergoil, J., Mialiier, D., Morel, J.M., Thoret, J.C., Vernet, G. (2017). *Volcanology of the Chaine des puys, 6me édition, Parc Naturel Régional des Volcans d'Auvergne.* [Mapa]. 1:25000. Francia.Parc naturel régional des Volcans dÁuvergne.

Boivin, P., Bourdier, J.L., Camus, G. *et al.* (1982). Influence de la Nature des Magmas sur l'Activité Phréatomagmatique: Approche Volcanologique et Thermodynamique. *Bulletin of Volcanology*, 45, 25–39. doi: **https://doi.org/10.1007/BF02600387**

Boivin, P., Miallier, D., Cluzel, N., Devidal, J.L., Dousteyssier, B. (2015). Building and ornamental use of trachyte in the center of France during antiquity: Sources and criteria of identification. *Journal of Archaeological Science: Reports*, 3, 247-256. doi: **https://doi.org/10.1016/j.jasrep.2015.06.017**

Bourgeois, L. (2013). Castrum et habitat des élites (France et ses abords, vers 880-vers 1000). En A. D. Iogna-Prat, M. Lauwers, F. Mazel et I. Rosé (Eds.), *Cluny, le monachisme et l'émergence d'une société seigneuriale* (pp. 463-487) Presses universitaires de Rennes.

Canuto, M. A., Estrada-Belli, F., Garrison, T. G., Houston, S. D., Acuña, M. J., Kováč, M., Marken, D., Nondédéo, P., Auld-Thomas, L., Castanet, C., Chatelain, D., Chiriboga, C. R., Drápela, T., Lieskovský, T., Tokovinine, A., Velasquez, A., Fernández-Díaz, J. C., & Shrestha, R. (2018). Ancient lowland Maya complexity as revealed by airborne laser scanning of northern Guatemala. *Science*, 361(6409), eaau0137. doi: **https://doi.org/10.1126/science.aau0137**

Castañeda, A. (2023). Interactions et mobilités entre la vallée du Lerma et les zones lacustres de Michoacán, Mexique. Le point de vue de productions céramiques [PhD Thesis]. Université Paris.

Charbonnier, P. (1982). Une autre France. La seigneurie rurale en Basse-Auvergne du XIVe au XVIe siècle. *Annales. Economies, sociétés, civilisations*, 37(2), 376-378

Contejean, M. (1864). Un castellum gaulois de l'Auvergne. Revue Archéologique, 10, 484-487.

Descola, P. (2005). *Par-delà nature et culture*. Gallimard.

Dirección de Estadística del Territorio Nacional (DETENAL) (1979). Carta Edafológica E14A11 Zacapu, [Mapa]. 1:50 000. Comisión de Estudios del Territorio Nacional, México.

Dorison, A. (2019). *Archéologie des systèmes agraires préhispaniques de la région de Zacapu, Michoacán, Mexique.* [Thèse de Docteur] Université Paris, Panthéon Sorbonne.

Dorison, A. (2020). Aménagements agraires préhispaniques dans un milieu volcanique: Analyses des données LiDAR du Malpaís de Zacapu, Mexique. *Archéologies Numériques*, 4(1), 1-15. doi: **https://doi.org/10.21494/ISTE.OP.2020.0523**

Dorison, A. (2022). Ancient Agriculture on Lava Flows: Using LiDAR and Soil Science to Reassess Prehispanic Farming on Malpaís Landforms in West Mexico. *Journal of Ethnobiology*, 42(2). doi: **https://doi.org/10.2993/0278-0771-42.2.131**

Dorison, A. (2023a). Verificación en el sitio Mich. 465 Los Camellones y sondeo edafológico de control fuera del sitio. En A. Pereira *et al.* (Eds.), *Proyecto Uacúsecha. Informe técnico sobre los trabajos de campo llevados a cabo en la región de Zacapu, Michoacán (2022).* Consejo de Arqueología at the INAH. Centre National de Recherche Scientifique.

Dorison, A. (2023b). Estudio arqueopedológico del sitio urbano de Mich. 38 El Infiernillo. En A. Pereira *et al.*(Eds.), *Proyecto Uacúsecha. Informe técnico sobre los trabajos de campo llevados a cabo en la región de Zacapu, Michoacán (2022).* Consejo de Arqueología at the INAH. Centre National de Recherche Scientifique.

Dorison, A., & Siebe, C. (2023). Evolution of ancient farming systems and demography in the volcanic highlands of Zacapu: A model drawn from Geoarchaeology and archaeogeography. *Ancient Mesoamerica,* 34(3), 771-796. doi: **https://doi.org/10.1017/S0956536122000013**

Dorison, A., Siebe Grabach, C., Elliott, M., & Pereira, G. (2022). A LiDAR-based geopedologic approach to address prehispanic agricultural landscapes in Northern Michoacán, West Mexico. *Boletín de La Sociedad Geológica Mexicana*, 74(3), A180622. doi: **https://doi.org/10.18268/BSGM2022v74n3a180622**

Ferrari, L., Orozco-Esquivel, T., Manea, V., & Manea, M. (2012). The dynamic history of the Trans-Mexican Volcanic Belt and the Mexico subduction zone. *Tectonophysics,* 522–523, 122–149. doi: **https://doi.org/10.1016/j.tecto.2011.09.018**

Fisher, C. T., & Leisz, S. E. (2013). New Perspetives on Purépecha Urbanism Through the Use of LiDAR at the Site of Angamuco, Mexico. In C.C. D. C. Comer & M. J. Harrower (Eds.), *Mapping archaeological landscapes from space.* (pp. 199-210) Springer.

Forest, M. (2023). The big picture: Reassessing population estimates and socio-spatial structure at the Zacapu Malpaís urban settlements using LiDAR. *Ancient Mesoamerica*, 1–19. doi: **https://doi.org/10.1017/S0956536121000389**

Forest, M. (Ed.). (2020). *El Palacio: Historiography and new perspectives on a pre-Tarascan city of northern Michoacán, Mexico*. Archaeopress Access Archaeology.

Fournier, G., & Fournier, P. F. (1983). La vie pastorale dans les montagnes du centre de la France. *Bulletin Historique et Scientifique de l'Auvergne Clermont-Ferrand*, 91(676), 199-358.

Fournier, G., Grelois, E. (2023). *L'étang du Fung, commune d'Olby. Notes historiques sur l'évolution du peuplement et des paysages de la chaîne des Puys.* Les forts villageois d'Auvergne.

Fournier, P. F. (1979). Ruines de villages bâtis à pierre sèche et abandon-

nés. *Bulletin historique et scientifique de l'Auvergne*, 89(660), 235-311.

Gaime,S. (2012). De la difficulté à distinguer le noble et l'ignoble. Exemple de deux sites médiévaux de l'Allier. *Archéopages*, 34, 58-60.doi : **https://doi.org/10.4000/archeopages.398**

García Cook, Á. (2008). Cantona: The City. In A. W. T. Sanders, A. G. Mastache, & Á. García Cook (Eds.), Urbanism in Mesoamerica-Urbanismo en mesoamérica. Instituto Nacional de Antropologia e Historia ; The Pennsylvania State University.

García, E. (2004). *Modificaciones al sistema de clasificación climática de Köppen.* Universidad Nacional Autónoma de México.

Gougeon, O. (1991). El noroeste de Michoacan: Un paisaje en busca de identidad. In C. Reyes & O. Gougeon (Eds.), Paisajes rurales en el norte de Michoacán. (pp. 53-101) Centro de estudios mexicanos y centroamericanos.

Hasenaka, T., & Carmichael, I. S. (1985). The cinder cones of Michoacán-Guanajuato, central Mexico: their age, volume and distribution, and magma discharge rate. *Journal of Volcanology and Geothermal Research*, 25(1-2), 105-124. doi: **https://doi.org/10.1016/0377-0273(85)90007-1**

Healan, D. M., & Cobean, R. H. (2012). Tula and The Toltecs. In D. L. Nichols & C. A. Pool (Eds.), *The Oxford handbook of Mesoamerican archaeology* (pp. 372-384). Oxford University Press.

Hers, M.-A. (1989). *Los toltecas en tierras chichimecas.* Universidad Nacional Autónoma de México, Instituto de Investigaciones Estéticas.

Jadot, E. (2016). *Productions céramiques et mobilités dans la région tarasque de Zacapu (Michoacán, Mexique) Continuités et ruptures techniques entre 850 et 1450 apr. J.-C.* [Thèse de doctorat] Université Paris.

Kokalj, Ž., & Somrak, M. (2019). Why Not a Single Image? Combining Visualizations to Facilitate Fieldwork and On-Screen Mapping. *Remote Sensing*, 11(7), 747. doi: **https://doi.org/10.3390/rs11070747**

Labat, J. N. (1995). *Végétation du nord-ouest du Michoacan, Mexique.* CEMCA, ORSTOM, Instituto de Ecología.

Ledger PM, Miras Y, Poux M, Milcent PY (2015. The Palaeoenvironmental Impact of Prehistoric Settlement and Proto-Historic Urbanism: Tracing the Emergence of the Oppidum of Corent, Auvergne, France. *PLoS ONE*, 10(4), e0121517. doi: **https://doi.org/10.1371/journal.pone.0121517**

Lefebvre, K., Dorison, A., & Urquijo Torres, P. (2023). Pueblos viejos–pueblos nuevos: Transformación del paisaje en el norte de Michoacán (México) a inicios del período novohispano (siglo dieciséis). *Ancient Mesoamerica*, 1–21. doi: **https://doi.org/10.1017/S0956536121000584**

Maccaferri, F., Rivalta, E., Keir, D. *et al.* (2014) Off-rift volcanism in rift zones determined by crustal unloading. *Nature Geoscience*,7, 297–300. doi: **https://doi.org/10.1038/ngeo2110**

Mahgoub, A. N., Reyes-Guzmán, N., Böhnel, H., Siebe, C., Pereira, G., & Dorison, A. (2017). Paleomagnetic constraints on the ages of the Holocene Malpaís de Zacapu lava flow eruptions, Michoacán (México): Implications for archeology and volcanic hazards. *The Holocene*, 28(2), 229–245. doi: **https://doi.org/10.1177/0959683617721323**

Martel C., Champallier, R., Prouteau, G, Pichavant, M., Arbaret, R., Balcone-Boissard, H., Boudon, G., Boivin, P., Bourdier, J.L., Scaillet, B. (2013). Trachyte Phase Relations and Implication for Magma Storage Conditions in the Chaîne des Puys (French Massif Central), *Journal of Petrology*, 54(6), 1071–1107. doi: **https://doi.org/10.1093/petrology/egt006**

Merle, O., & Michon, L. (2001). The formation of the West European Rift; a new model as exemplified by the Massif Central area. *Bulletin de la Société Géologique de France*, 172 (2), 213-221. doi: **https://doi.org/10.2113/172.2.213**

Michelet, D. (2013). Cerámicas del Centro-Norte de Michoacán entre el Clásico y el Posclásico. In C. Pomédio, G. Pereira, & E. Fernandez-Villanueva (Eds.), *Tradiciones cerámicas del Epiclásico en el Bajío y regiones aledañas: Cronología e interacción: Cronología e interacción.* University of Michigan Press. doi: **https://doi.org/10.30861/9781407311371**

Michelet, D. (1992). *El proyecto Michoacán 1983-1987. Medio ambiente e introducción a los trabajos arqueológicos.* Centre d'Etudes Mexicaines et Centramericaines.

Michelet, D., Pereira, G., & Migeon, G. (2005). La llegada de los uacúsechas a la región de Zacapu, Michoacán: Datos arqueológicos y discusión. In L. Manzanilla (Ed.), *Reacomodos demográficos: Del clásico al posclásico en el centro de México.* Universidad Nacional Autónoma de México, Instituto de Investigaciones Antropológicas.

Michelin, Y. (1996). *Les jardins de Vulcain: Paysages d'hier, d'aujourd'hui et de demain, dans la chaîne des Puys du Massif central français.* Maison des sciences de l'homme.

Michelin, Y., Vergne, V., Cougoul, C., & Cournut, S. (2001). Variations des teneurs en éléments minéraux dans un bas marais holocène : la Vezolle (Chaîne des Puys), première recherche des manifestations anthropiques. *Quaternaire*, 12 (1-2), 31-41.

Michelin, Y., Vergne, V., Denefle, M., & Cohen, J. (1996). Méthodologie pour une reconstitution paysagère: un exemple dans la chaîne des Puys, de la fin de l'Empire romain au XIIIe siècle. *Actes des congrès de la Société d'Archéologie Médiévale*, 5(1), 57-62.

Miras, Y., Laggoun-Défarge, F., Guenet, P. *et al.* (2004). Multi-disciplinary approach to changes in agro-pastoral activities since the Sub-Boreal in the surroundings of the "narse d'Espinasse" (Puy de Dôme, French Massif Central). *Vegetation History and Archaeobotany*, 13, 91–103. doi: **https://doi.org/10.1007/s00334-004-0033-z**

Pereira, G. (2007). Le destin post-mortem du guerrier: Pratiques funéraires et statut social dans le Michoacán ancien, Mexique. In L. Baray, P. Brun, & A. Testart (Eds.), *Pratique funéraire et sociétés: Nouvelles approches en archéologie et en anthropologie sociale* (pp. 371-390) Actes du colloque interdisciplinaire de Sens.

Pereira, G., Dorison, A., Quezada Ramírez, O., Gillot, C., & Michelet, D. (2023). Nueva perspectiva sobre el sistema de organización territorial epiclásico en la región de Zacapu, Michoacán. *Ancient Mesoamerica*, 1–24. doi: **https://doi.org/10.1017/S0956536121000651**

Pereira, G., Forest, M., & Jadot, E. (2020b). Ephemeral Cities? The Longevity of the Postclassic Tarascan Urban Sites of Malpaís de Zacapu and its Consequences on the Migration Process. In M.-C. Arnauld, C. S. Beekman, & G. Pereira (Eds.), *Mobility and migration in ancient Mesoamerican cities.* University Press of Colorado.

Pereira, G., Michelet, D., Dorison, A., Faugère, B., Quezada Ramírez, O., Lefebvre, K., Forest, M., Medina, I., Barrientos, I., Goudiaby, H., Barba, L., Blanca, J., Ortiz, A., & Gillot, C. (2016). *Proyecto Uacúsecha. Informe técnico sobre los trabajos de campo llevados a cabo en Malpaís Prieto y otros asentamientos de la región de Zacapu.* Consejo de Arqueología at the INAH. Centre National de Recherche Scientifique.

Pereira, G., Michelet, D., Gillot, C., Barrientos, I., Quezada Ramírez, O., & Huerta, A. (2020a). *Proyecto Uacúsecha. Informe técnico sobre los trabajos de campo llevados a cabo en la región de Zacapu, Michoacán. Temporada 10 (2018-19)*. Consejo de Arqueología at the INAH. Centre National de Recherche Scientifique.

Pétrequin, P. (1994). *Ocho mil años de la Cuenca de Zacapú: Evolución de los paisajes y primeros desmontes.* Centro de estudios mexicanos y centroamericanos. doi: **https://doi.org/10.4000/books.cemca.2340**

Piña Chan, R. (1975). *Teotenango. El antiguo lugar de la muralla.* Gobierno del Estado de México.

Poisson J.-M. (2007), *Mottes castrales et autres fortifications médiévales de terre et de bois : état de la question en France.* Motte-Turmhügelburg-Hausberg.

Pollard, H. P. (2008). A model of the emergence of the tarascan state. *Ancient Mesoamerica,* 19(2), 217–230. doi: **https://doi.org/10.1017/S0956536108000369**

Quezada Ramírez, O., & Darras, V. (2023). Caracterización espacial de un paisaje de extracción prehispánico: El yacimiento de dacita de Las Minas, Zacapu, Michoacán. *Ancient Mesoamerica,* 1–29. doi: **https://doi.org/10.1017/S0956536122000025**

Reyes-Guzmán, N., Siebe, C., Chevrel, M. O., & Pereira, G. (2021). Late Holocene Malpaís de Zacapu (Michoacán, Mexico) andesitic lava flows: Rheology and eruption properties based on LiDAR image. *Bulletin of Volcanology*, 83(4), 28. doi: **https://doi.org/10.1007/s00445-021-01449-0**

Reyes-Guzmán, N., Siebe, C., Chevrel, M. O., Guilbaud, M.-N., Salinas, S., & Layer, P. (2018). Geology and radiometric dating of Quaternary monogenetic volcanism in the western Zacapu lacustrine basin (Michoacán, México): Implications for archeology and future hazard evaluations. *Bulletin of Volcanology*, 80(2), 18. doi: **https://doi.org/10.1007/s00445-018-1193-5**

Rojas Rabiela, T. (1988). Las Siembras de Ayer: La agricultura indígena del siglo XVI. SEP.

Rostain, S., Dorison, A., De Saulieu, G., Prümers, H., Le Pennec, J.-L., Mejía Mejía, F., & Descola, P. (2024). *Two Thousand Years of Garden Urbanism in the Upper Amazon*. Science. 383, 183-189. doi: **https://doi.org/10.1126/science.adi631**

Surmely, F., le Junter J. (2017). Les structures pastorales des massifs du Sancy et du Cézallier (Puy-de-Dôme, France). *Revue archéologique du Centre de la France*, 56(63).

Tournadre, M. (2017). *Le « Camp des Chazaloux », Villevieille : étude documentaire.* Association Terre Ancienne, 85 p.

Vivent, D., & Vernet, G. (2001). Apport de la palynologie à l'étude des retombées volcaniques tardiglaciaires et holocènes de la Chaîne des Puys enregistrées en Limagne (France). *Tephras, Chronology, Archaeology*, 1, 255-262.