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Geology of Lanzarote's northern region (Canary Island, Spain)

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ABSTRACT

This work presents a detailed volcano-geological map of the Northern region of Lanzarote (Canary Islands, Spain). This map is a synthesis of gathered and interpreted field data and geological maps. We have integrated information obtained from: (a) detailed geological field surveys, (b) high-resolution digital elevation models (DTMs), (c) aerial orthophotographs, (d) morphometric analysis of eruptive deposits and volcanic structure (i.e. lava tubes), and (e) integrated with data from previous publications (IGME – *Instituto Geológico y Minero de España*). This map provides a detailed view of the volcanic diversity of the region and an overview of the lava tube system of La Corona, both of which may be used as references for future research work.

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1. Introduction

The northern sector of Lanzarote constitutes a unique volcanic zone because, despite its relative maturity, the climatic conditions allowed for the favourable preservation of the ancient volcanic landforms. In terms of eruptive style and composition, the region hosts a wide variety of volcanic landforms, ranging from the Mio-Pliocene (10.2–3.8 Ma) basaltic plateau of Famara to the Pleistocene tephra cones of the Los Helechos-La Corona-La Quemada alignment (91–21 ka). As a result, a wide variety of deposits and volcanic structures, including lava flows, pyroclastic deposits, lava tubes and tumuli, were formed and preserved. In addition, the region hosts one of the biggest lava tubes on Earth, the La Corona lava tube system (Carracedo et al., 2003; Crawford, 1996; Montoriol-Pous & De Mier, 1969; Tomasi et al., 2022) originated by the homonym volcano La Corona [29.184656, −13.483496].

The northernmost region of the island of Lanzarote is covered by three separate geological maps scaled 1:25.000. Published by the Spanish Geological Survey (IGME-CSIC), those maps describe separate portions of the area presented here: 1080-I-IV (*Caleta del Sebo*) (Balcells & Barrera, 1993b); 1080-II (*Sòo*) (Gómez & Barrera, 1993) and 1080-III (*Haría*) (Balcells & Barrera, 1993a).

This work aims to deliver a unified geological map (Main Map) of the region along with two cross-sections, showing the distribution, chrono-stratigraphy, and composition of the main volcanic units, which may be used as a guidance for additional research in the area.

2. Geological setting

2.1. The Canary Islands

The Canary Islands archipelago is a Spanish autonomous community located 100 km west of Morocco and more than 1000 km south of continental Spain. It is the easternmost archipelago of the Macaronesia group (Rijsdijk et al., 2014; Rodriguez-Gonzalez et al., 2018), along with the Azores, Madeira, Selvagens, and Cape Verde. This region is situated in the north-western part of the African plate, at a transitional zone, between continental and oceanic crust. The Canaries comprise an elongated chain of seven major volcanic islands, numerous islets, and seamounts (Hoernle & Carracedo, 2009; Tomasi et al., 2022; Figure 1).

The volcanic activity in the Canary Islands is linked to a deep mantle plume (King, 2007; King & Adam, 2014; Montelli et al., 2004, 2006; Negredo et al., 2022) which originated the *Canary Islands Seamounts Province* (CISP) (Ancochea et al., 1996; Carracedo et al., 1998; Dañobeitia & Canales, 2000; Duncan, 1984; Morgan, 1983; van den Bogaärd, 2013), and

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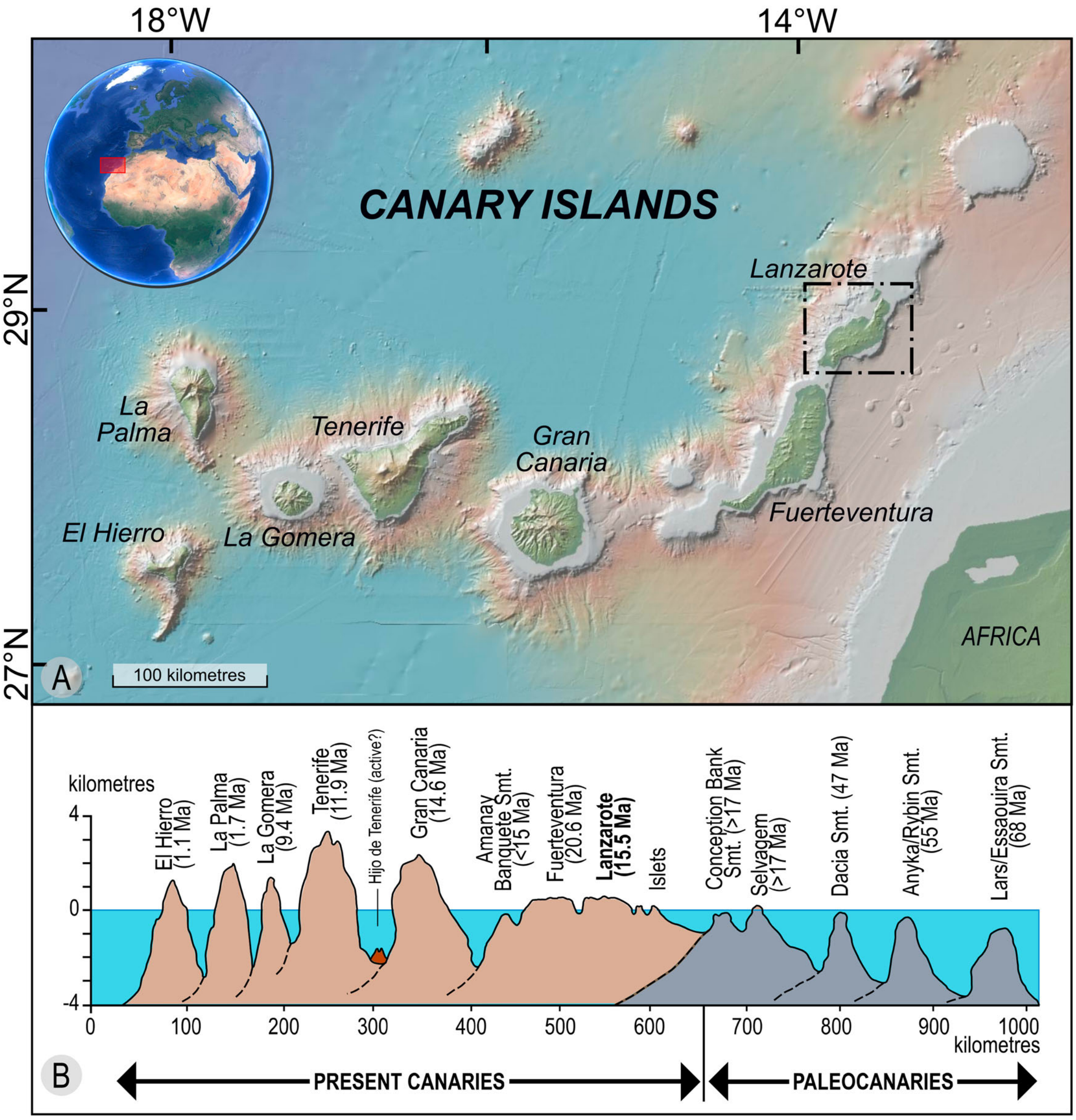

Figure 1. Geographic setting of the Canary Islands. (A) The Canarian archipelago, including the main islands and the associated seamounts. The frame highlighted the island of Lanzarote. The inset shows the location of the archipelago in the eastern Atlantic Ocean. Map constructed with GeoMapApp (https://www.geomapapp.org). (B) Schematic diagram showing the chain of islands and seamounts that form the Canary Volcanic Islands Province. The ages decrease toward the southwest, from Lars/Essaouira Seamount (68 Ma) to El Hierro (1.12 Ma) (modied from Rodriguez-Gonzalez et al., 2018).

may well have been activated or re-activated by the transit of the African plate over the plume in early to mid-Eocene and Miocene (Greensmith, 2000).

The formation ages of each island show an irregular eastward movement of the plate above the hotspot due to oceanic crust spreading occurring at the mid-Atlantic ridge (Figure 1). The lack of a coherent age-distance correlation within hotspot-related archipelagos in slow-moving plates (ca. 9 mm/yr), such as the Canarian archipelago (Figure 1(A)), is an effect of the long-term spatial focusing of volcanic activity within a constrained area (Meyzen et al., 2015).

2.2. Lanzarote

Lanzarote is the eastern-most island of the Canaries. It is 60 km long, 20 km wide, and the fourth largest island by surface area (862 km^2). Its formation started 15.5 Ma ago and, is the second oldest island of the archipelago after Fuerteventura (Figure 1(B)).

The topography of the island is characteristic of mature islands, with deeply eroded volcanic massifs, tall cliffs dominating the landscape, and U-shaped valleys, due to the accumulation of younger detritic infill at the base of the original V-shaped valleys (Troll & Carracedo, 2016). Despite its early formation, Lanzarote is still considered volcanically active, with two historical eruptive episodes recorded between 1730 and 1736 at Timanfaya, and in 1824 at Tao and Tinguatón, in a northwestern-southeastern trending rift zone located in the middle of the island (Figure 2) with a northeast–southwest trend (Cabrera Vega, 2010; Hansen Machín & Pérez Torrado, 2005; Troll & Carracedo, 2016).

Figure 2. Simplified geological map of the of the geological evolution of Lanzarote. Modified from Hoernle and Carracedo (2009) and Tomasi et al. (2022). Insert map showing the mapping sources 1080-I–IV Balcells and Barrera (1993b); 1080-III Balcells and Barrera (1993a); 1080-II Gómez and Barrera (1993). The dashed insert indicates the area covered by the Main Map.

The volcanic centres of Lanzarote prevalently develop along fissures with the same trend (Coello et al., 1992; Greensmith, 2000; Páez et al., 2002). This is indicative of the alignment of major subsurface fractures that in the past have allowed easier access for the ascending magmas. The direction of these fractures has largely governed the volcanic eruptions in Lanzarote until more recent times.

From a geological point of view, Lanzarote can be considered as the northern prolongation of Fuerteventura, since the two islands are only separated by a shallow strait of sea, *La Bocaina* (40 m water depth, Figure 1(B)). During earlier glacial times of marine regression, there was probably a land bridge that connected the two islands (Coello et al., 1992; Hausen, 1959; Troll & Carracedo, 2016).

Most of the materials that constitute the island of Lanzarote are lava flows, pyroclastic products, necks and dikes of alkaline to tholeiitic basaltic composition, emitted during several cycles of intense volcanic activity separated from each other by periods of quiescence and intense subaerial erosion. These volcanic cycles were referred as Series by Fúster et al. (1968) and are described in the following sections. In particular the volcanism represented in the Main Map belongs to Series I of the Upper Pliocene and Series IV-A of the Pleistocene, that will be covered in much more detail.

2.2.1. Mio-Pliocene

Series I (Figure 2 in blue shades) consists of the oldest volcanic material on the island and formed extensive plateaus with a surface area once larger than the current island and several hundred of metres thick. The effusive activity started in the southern region of island, during the mid-Miocene (ca. 15.5 Ma), and lead to the emplacement of the Los Ajaches volcanic shield.

During the upper Miocene, volcanism shifted to the north-east, forming the Famara volcanic shield, which nowadays characterises most of the northern region of Lanzarote. The 400 m high and 20 km long west-facing Famara cliffs (or *Risco de Famara*, Figure 3(A)), expose a section of the partially-eroded Famara shield (Greensmith, 2000; Hausen, 1959; Páez et al., 2002). The *Risco de Famara* cliff border an elevated plateau (altitude: 500–600 m), with a culminating summit at *Peñas del Chache*, which is the Lanzarote's highest peak at 671 m (Greensmith, 2000; Hausen, 1959; Páez et al., 2002; Troll & Carracedo, 2016). The scarp reveals alkali basalts that accumulated during the shield emplacement. These basalts are interleaved with continental sediments (as caliche and eolian sands) which deposited during inactive periods. The base of the series is crossed by dikes of trachytic composition.

Famara massif. It is the northern and youngest main shield volcano of the island, and extends for about 20 km from Punta Fariones in the north to the proximity of Teguise in the south, with degrading elevations southwards. Originally, the edifice was extending further to the west, where nowadays is the *Risco de Famara*. The missing portion of this volcanic edifice is most likely the result of a lateral collapse of its western flank followed by an extensive erosion, as suggested by a large Pleistocene-Holocene marine abrasion platform (Carracedo, 1994; Páez et al., 2002; Troll & Carracedo, 2016). The platform is located where the narrow strait of El Rio separates the main-island from the island of La Graciosa.

The *Risco de Famara* cliffs expose a sub-horizontal ESE-dipping basaltic lava flows, interleaved by layers and horizons of soils and caliche, and volcanoclastic materials (Hausen, 1959; Páez et al., 2002).

According to Fúster et al. (1968), Series I corresponds to the majority of the massif. The Series I has been further subdivided into three minor sequences: the *Lower Famara formation (I-A)*, 10.2–8.7 Ma, and the *Middle Famara formation (I-B)*, 6.5–5.7 Ma, both Miocene in age, and the Pliocene *Upper Famara formation* (I-C), 3.9–3.8 Ma, (Carracedo & Rodríguez Badiola, 1992; Coello et al., 1992; Fúster et al., 1968; Greensmith, 2000; Hausen, 1959). These three superimposed cycles seem to have been separated by long intervals of time (≥2 Ma each) during which the volcanic activity waned or stopped completely (Coello et al., 1992; Fúster et al., 1968; Greensmith, 2000; Hausen, 1959).

- The *Lower Famara formation* (I-A), which consists of basaltic flows interleaved with pyroclastic levels, has the greatest surface extension within the region. Individual pyroclastic levels in this sequence can reach 1–3 m, whereas the total thickness of this formation is 200 m. The lava flows are crosscutted by several dikes feeding the emission centres. Important deposits of aeolian sands, marine deposits, and caliche, within this sequence, are indications of long periods of inactivity. These strata are easily recognisable, because of their high fossiliferous content, which mostly consists of terrestrial gastropods, bird and tortoise remnants (Lomoschitz et al., 2016; Troll & Carracedo, 2016). One of the most well-known discoveries are some large eggshells, (Franz Sauer & Rothe, 1972; Lomoschitz et al., 2016; Rothe, 1964; Schmincke, 1976), recently attributed to flying birds from the order of *odontopterygiform*, a late progenitor of the pelicans, albatrosses and cormorants (Casañas, 1990; Páez et al., 2002; Troll & Carracedo, 2016).
- The *Intermediate Famara formation* (I-B) lays uncomformally on I-A. It is characterised by frequent pyroclastic cones and strata interlayered within lava flows. The basaltic flows are massive and porphiric, with phenocrystals of iddingsitised olivine (Páez et al., 2002; Tomasi et al., 2022). The vacuoles are generally filled with zeolites and carbonates.
- The *Upper Famara formation* (I-C), consists of massive ʻaʻā-type flows, piled on top of each other, and frequently displaying well-developed columnar disjunction. During this volcanic cycle, the maximum subaerial growth of the massif took place (Ancochea et al., 1993). This formation covers only the high elevation areas and has less horizontal extent than the previous two. This section of the serie is characterised by the presence of different pyroclastic levels interlayered among the massive lava flows.

Basaltic lavas of the three Famara formations have remained similar in genetic and compositional characteristics throughout the whole eruptive history (Armenti et al., 1989; Carracedo & Rodríguez Badiola, 1992). The long period of quiescence (ca. 2.5 Ma) in the north between the end of the emplacement of the Series I and the first Pleistocene eruptions (i.e. Series IV-A see section 2.2.3 – Fúster et al., 1968; Páez et al., 2002), was marked by intense erosion processes which led to significant degradation and dismantling (Coello et al., 1992; Greensmith, 2000; Hansen Machín & Pérez Torrado, 2005; Hausen, 1959).

2.2.2. Early Pleistocene

All volcanic activity in the northern region of the island ceased at the end of the Famara activity, approximately 4 million years ago, followed by a period of intense erosion. During that period, the

Figure 3. Lanzarote's northern lava tubes. (A) View from La Salina del Rio of lava cascades along the Famara cliff, looking southwards (Photo: M. Tonello); (B) depicts the termination of the crusted-over lava tube in the distal end of the lava falls, see Figure 5 (A) (Photo: I. Tomasi). (C, D) Internal sections of the La Corona lava tube: (C) shows a layer of pyroclastic material (white arrow) visible along the tube walls (Photo: I. Tomasi), whereas (D) displays peculiar internal morphologies such as a *flow ledge* (or bench) at the tube side and, at the floor level, a small tube-in-tube structure (Photo: R. Shone). (E, F) Internal pictures of the lava tube at Cuevas de Máguez (Photo: I. Tomasi).

relief was profoundly altered, and the building was largely excavated by valleys and ravines. Between the late Pliocene and the Early Pleistocene, a new volcanic period began. It was manifested along a NE-SW alignment of emission centres and volumetrically less important than the one of Famara complex.

Series II (Figure 2 in dark green). After almost 2.5–3 Ma of inactivity, large cinder and tuff cones, and basaltic lavas formed the volcanic groups of Teguise-Caldera Riscada and Montaña Roja (1.6–0.7 Ma) which are heavily degraded by the subsequent exogenic erosion. Series II includes the *La Atalaya de Haría-Mala alignment*, a set of emission centres that arose in the southern ravines excavated in the Famara Mio-Pliocene relief, and were responsible of 'intracanyon' lava flows, in some cases, reaching the coast. Both edifices are currently dismantled in their upper parts, but the morphology of a filled circular crater can still be recognised.

Series III (Figure 2 in yellow) is covering the main central area of the island of Lanzarote and was formed by the effusive episodes of the Central rifting and the Rubicon platform (<0.9 Ma). It is constituted by abundant basaltic lavas with large, well-preserved cinder cones, covered by caliche. Within this serie are *Las Calderas de Guatiza alignment* constituted by several volcanic vents with a SE orientation which can be found in the present-day Valley of Guatiza. This group of volcanoes is structurally continuous, and constitute the northern end of this alignment that develops along 45 km from Montaña Roja in the island's south (Hansen Machín & Pérez Torrado, 2005).

2.2.3. Late Pleistocene

PLEISTOCENE-HOLOCENE – Series IV (Figure 2 in pink shades). It consists of basaltic lavas and cinder cones (ash and lapilli cones) which were not covered by caliche. The IV Series can be subdivided into two main events: (IV-A) the Pleistocene volcanic alignment of Los Helechos-La Corona-La Quemada (91–21 ka) in the northern region, and (IV-B) the late Historical eruptions (1730-36 and 1824) in the central region.

The Quaternary reactivation occured preferentially along existing NE-SW trending set of fractures, characteristic of Lanzarote. During this phase (i.e. Series IV-A – Fúster et al., 1968) the majority of the island surface was flooded by a large outpouring of basaltic lava flows (Cabrera Vega, 2010; Carracedo et al., 2003; Coello et al., 1992; Hansen Machín & Pérez Torrado, 2005; van den Bogaārd, 2013).

The new volcanic activity led to the formation of an alignment of volcanic edifices along an eruptive fissure, and covered the Famara Mio-Pliocene massif. This volcanic alignment (Serie IV-A) can be divided into three main volcanic complexes: Los Helechos, La Corona and La Quemada de Orzola. Radioisotope dating obtained by Carracedo et al. (2003) and the more eroded and altered character of the lavas indicate that La Quemada de Orzola and Los Helechos lavas are the oldest episodes of the series dating back to 91 ka; instead with its 21 ka La Corona volcano is the youngest of the edifices (Carracedo et al., 2003; Hansen Machín & Pérez Torrado, 2005; Hoernle & Carracedo, 2009). In order to better describe the area, we divided the relevant units into the homonymous Pleistocene volcanic centres, identifying each with a specific colour.

Los Helechos complex. A set of several overlapping volcanic cones aligned along the NE-SW oriented fissure, with a total length of ∼1.8 km. While some of these edifices were buried throughout the evolution of the volcanic complex build-up some were better preserved (Balcells & Barrera, 1993a, 1993b; Gómez & Barrera, 1993), such as La Quemada de Máguez, El Helecho, and La Cerca. From the north-western side of the Los Helchos group, the lava initially infilled the nearby Guinate valley, located right below, and then continued down-hill, off the Famara cliffs to the western coast through a small opening in the relief (Carracedo et al., 2003; Tomasi et al., 2022; Troll & Carracedo, 2016). At the bottom of the cliff, the lava form a fan, widening for several tens of metres out to sea. However, the majority of the lava flowed towards east and south-east, flooding the valley of Máguez and reaching the eastern coast 5–6 km away from the edifice, where the towns of Arrieta and Punta Mujeres are nowadays located. This emplacement left an 'a'ā-type lava field, locally known as the *Malpaìs*. In the Los Helechos lava field, is known the existence of a network of lava tubes called Cuevas de Máguez (Smets & Santana Gómez, 2021), briefly described in section 2.2.2.1.

La Quemada de Orzola. Located on the north-eastern end of the volcanic alignment, it sits on the lava piles of the Famara massif, from where it rises about 100 m high. The volcano presents a peculiar horseshoe 350 m-wide crater open to the east which resulted from the partial outward collapse of the rim. The lava field of La Quemada was obliterated by nearby and more recent lava flows from La Corona. The only preserved lava flows of La Quemada are located in vicinity of the town of Orzola, at the foot of Famara eastern slope. There, lava flows were heavily reworked by anthropic activities and partially covered by alluvial deposits. Several boulders (avg. height 10 m) and tumuli-like structures are still visible (Figure 4(A)) in this area and known as the *Los Bolos de Orzola*.

La Corona. It is located at the top of the Famara-Guatifay plateau, from where it rises about 269 m high (total height of 609 m a.s.l.). The main crater has a circular shape, 400 m in diameter, while the secondary vent, developed over the eastern flank is just 100 m wide. At the foot of the eastern side of the edifice, a sinkhole is visible. From here the well-known lava tube of La Corona is thought to be originated (Figure 3(C, D), Tomasi et al., 2022). It runs

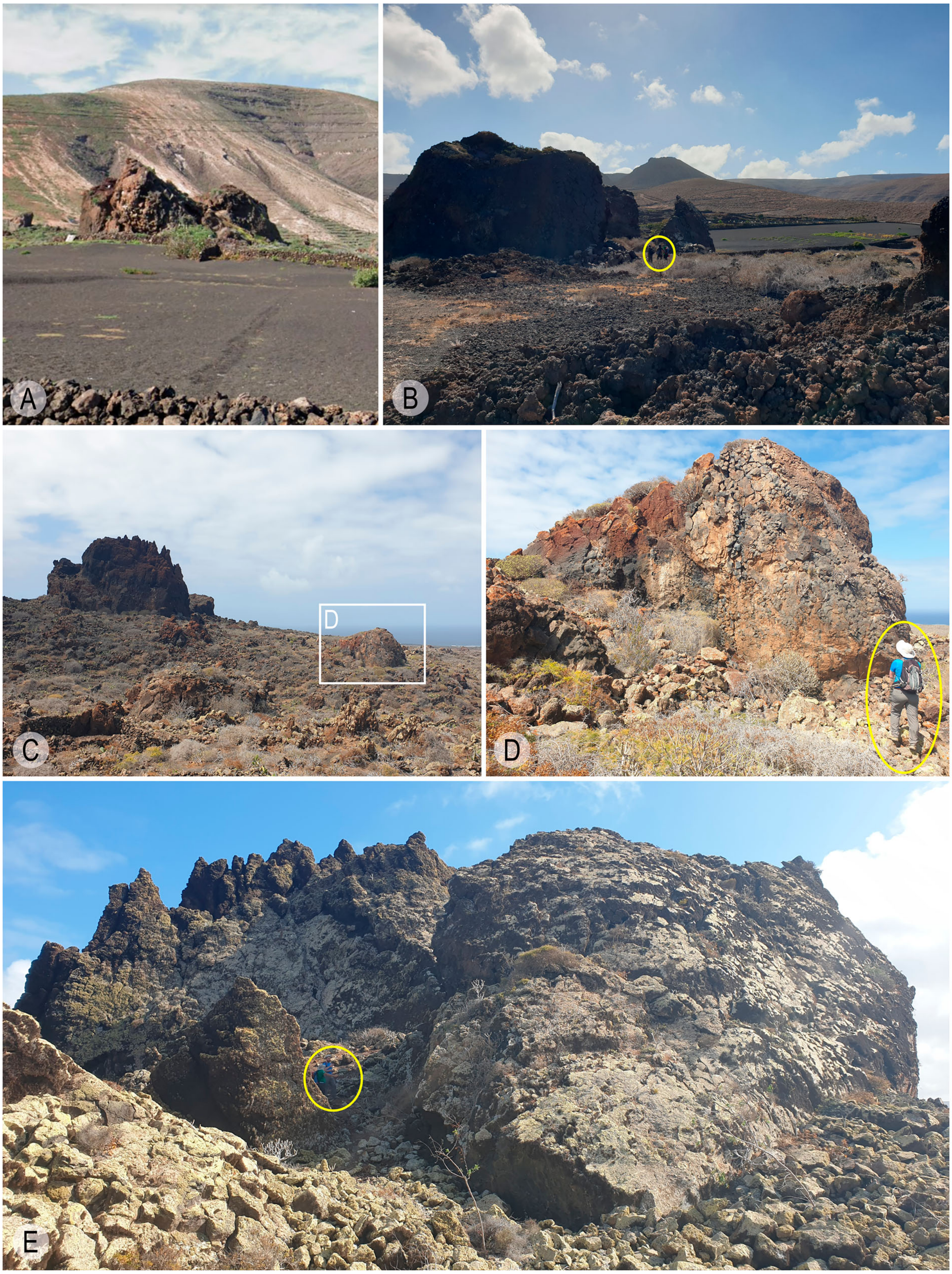

Figure 4. Tumuli-like structure, hornitos and large blocks spread throughout the malpaìs of La Quemada de Orzola, (A) one of the Bolos de Orzola visible along the LZ-203 [29.2046339, −13.4526539] (Photo: Google Earth) looking westwards, and La Corona: (B) Roque Vitillo [29.196316, −13.454124]; (C) a panoramic view of the southern side of Peña Grande [29.184638, −13.453081], the largest of the tumuli-like structures; (D) 'small bolo' close to Peña Grande. (E) A view of the northern side of Peña Granda. The big rock (avg. diameter of 35 m; avg. 20 m high) can be clearly seen from every point of the La Corona malpais. From the top, there is an excellent panoramic view of the volcanic plain. Photo: Ilaria Tomasi.

underneath the malpaìs for 6.1 km before it reaches the eastern coast and extends for other 1.6 km beneath the ocean.

Similarly to Los Helechos complex La Corona lavas were mainly channelled towards the east, but some of them flowed westwards, through the Famara cliff forming a small delta while entering to the sea. Towards the north, the La Corona flows overlap the lavas of previous effusive episodes, from La Quemada and the older Mio-Pliocene substratum, while in the south, they cover the previous lava flows from Los Helechos.

As described by Tomasi et al. (2022), La Corona lava flows and other late Pleistocene units show a slight differences in trace element compositions but a clear difference in morphology, thickness, phenocryst content and alteration state. In contrast to the Los Helechos lava flows which are massive, fractured, and displaying spheroidal weathering indicating rock-water interaction (e.g. onion skin shells – Chatterjee & Raymahashay, 1998; Ollier, 1971), the La Corona lava flows are typically more porous and thinner. On the field, their contact is marked by a layer of pyroclastic material interlaid between the lava flows of La Corona and Los Helechos. These pyroclasts correspond to the early stage of the Strombolian activity of La Corona, which covered the Los Helechos lava flows before the La Corona lava emissions occurred (Figure 3(C); Tomasi et al., 2022).

The la Corona lava flows form a chaotic ‘a’ā-type lava field, with large blocks and flows with very pronounced frontal and lateral slopes. A dozen of tumuli-like structures are found on the youngest lava flows of La Corona, such as *Peña Grande* and *Peña Redonda* (Figure 4). These large structures are formed by the pressurised injection of molten lava under the surface crust, lifting the crust in a dome-shape form. During the uplift, the crust of the cupola tends to form cracks that propagate along the cupola flanks,

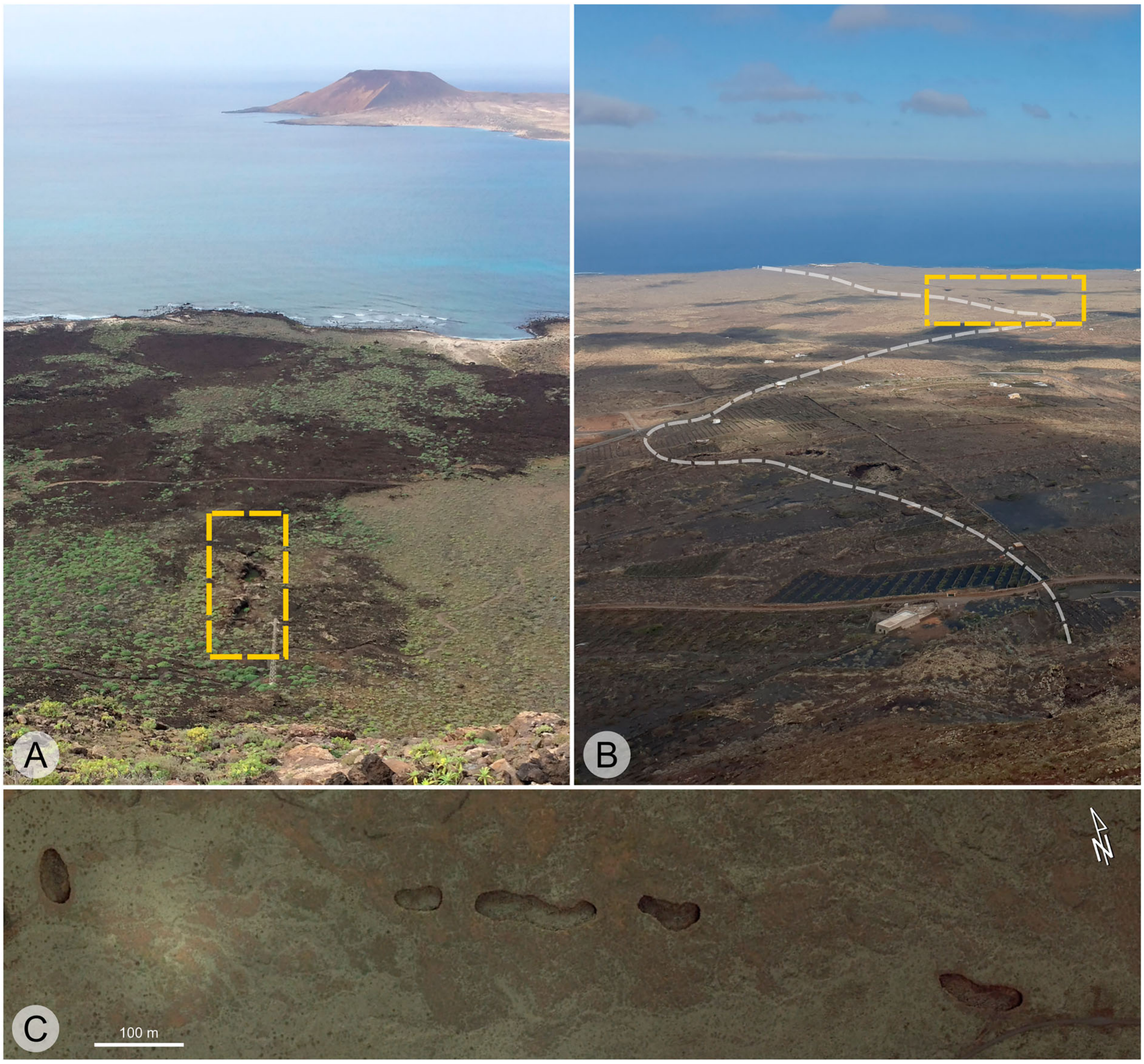

Figure 5. Skylights and collapses of lava tube ceilings. (A) Viewpoint on the La Corona lava cascade from the Risco de Famara, looking westwards, the frame emphatises the over-crusted lava tube (see Figure 3B). (B) Viewpoint on the La Corona Malpais from the crater rim, looking eastwards. The dotted line traces the tube path from the eastern side of the volcano toward the coast. The frame shows the location of the large collapses of the tube that are visible in (C), photo: Ilaria Tomasi. (C) Satellite image of the collapse chains of the La Corona lava.

allowing the leakage of the molten lava (Guest et al., 1984; Rossi & Gudmundsson, 1996; Voigt et al., 2021; Walker, 1991).

2.2.4. Lava tubes

Lava tubes are a peculiar variety of lava caves, typical of basaltic lava field. These roofed conducts are particularly effective thermal structures that allow channelised lava to be transported over great distances, due to the minimisation of heat loss.

Los Helechos. The most important network of lava tubes in the area of Los Helechos, is located at the contact between the Los Helechos malpaìs and La Corona malpaìs [29.164933, −13.468500], close to LZ-201. It is known as Cuevas de Máguez, or Cuevas de la Atalaya (Sauro et al., 2019; Smets & Santana Gómez, 2021). These braided tubes have long been known, but they have not been extensively explored up to date as they are situated on a private land. Roof sections of these tubes indicate a genetic mechanism of overcrusting with some segments probably initiated by shallow inflation. In contrast to the enormous La Corona lava tube, one of the biggest lava tube on Earth (Crawford, 1996; Montoriol-Pous & De Mier, 1969; Tomasi et al., 2022), the Máguez lava tube system is a small (tube section has an average length and width of 5 and 3 m respectively), labyrinthine lava tube network (Figure 3(E,F)). The tube is located slightly below the surface. It presents 4 entrances and a total cave development of 974 m (Smets & Santana Gómez, 2021). Few other small lava tubes are known in the area of Los Helechos lava flows. A series of three jameos can be observed to the south of the Corona tube close to Punta Mujeres [29.152279, −13.442592]. They provide access only to limited sections (few metres) of an ancient mainly collapsed conduit.

La Corona. The lava tube system of La Corona is listed among the biggest lava tubes on Earth (Bravo, 1964; Crawford, 1996; Fúster et al., 1968; Montoriol-Pous & De Mier, 1969; Sauro et al., 2019; Tomasi et al., 2022). Developed through an inflation process, the tube has a total length of about ∼7.6 km (∼9.7 km of total cave development) and an average width of 28 m (Figure 3(C,D), Bravo, 1964; Sauro et al., 2019; Tomasi et al., 2022). The tube path can easily be reconstructed following the '*Ruta de los Jameos*' (Bravo, 1964 - Figure 5(B)), and Figure 6) from the eastern side of the main volcanic edifice toward the coast, at Jameos del Agua (Tomasi et al., 2022). At Jameos del Agua [29.157571, −13.431390] begins the flooded portion of the tube, named *Tunnel del Atlantida* which runs below sea-level for 1.6 km (Carracedo et al., 2003; Isler, 1989; Mendo & Ortega,

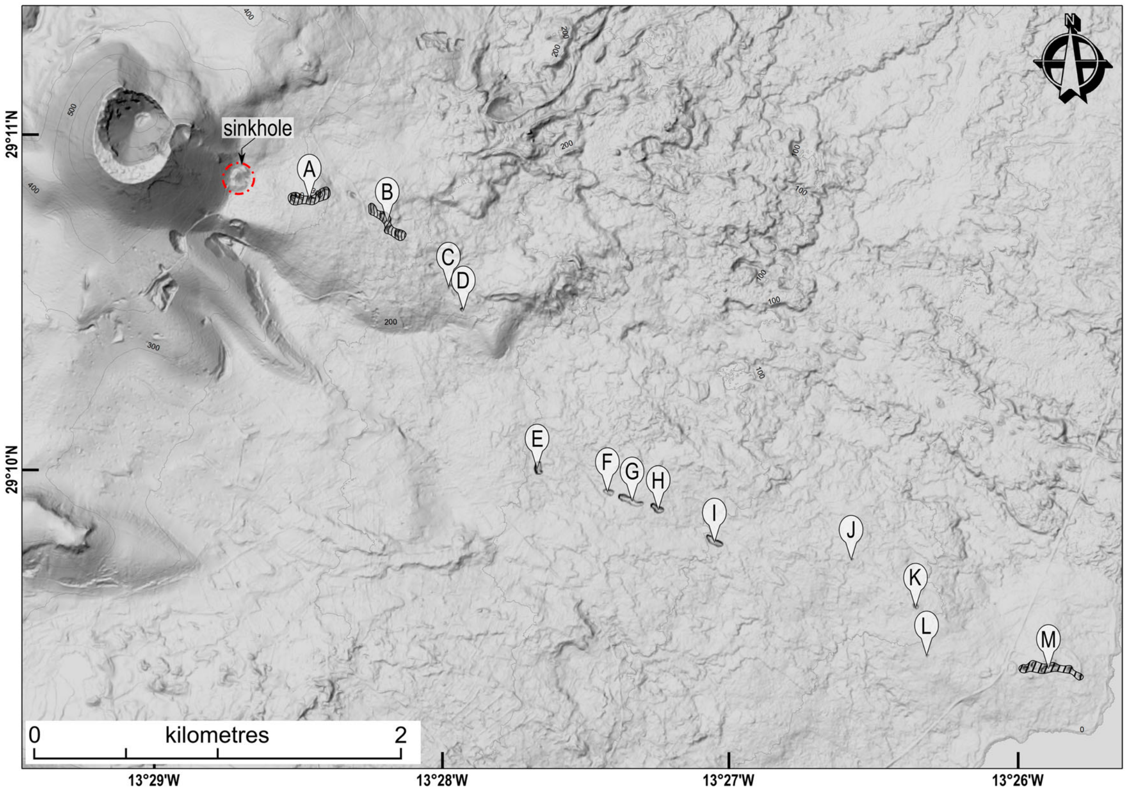

Figure 6. Plan-view of the La Corona tube system's lava field and skylights. (A) Jameos de los Molinos; (B) Jameos de Arriba; (C) Jameo de Francisco Leòn; (D) Jameo de los Prendes; (E) Jameo de la Gente; (F) Jameo Tacho; (G) Jameo Cumplido; (H) Jameo Agujerado; (I) Jameo de la Puerta Falsa; (J) Jameo Redundo; (K) Jameo de los Verdes; (L) Jameo de los Lagos; (M) Jameos del Agua. The adopted nomenclature is updated and sometimes differs from that utilised by Montoriol-Pous and De Mier (1969). Modified from Tomasi et al. (2022).

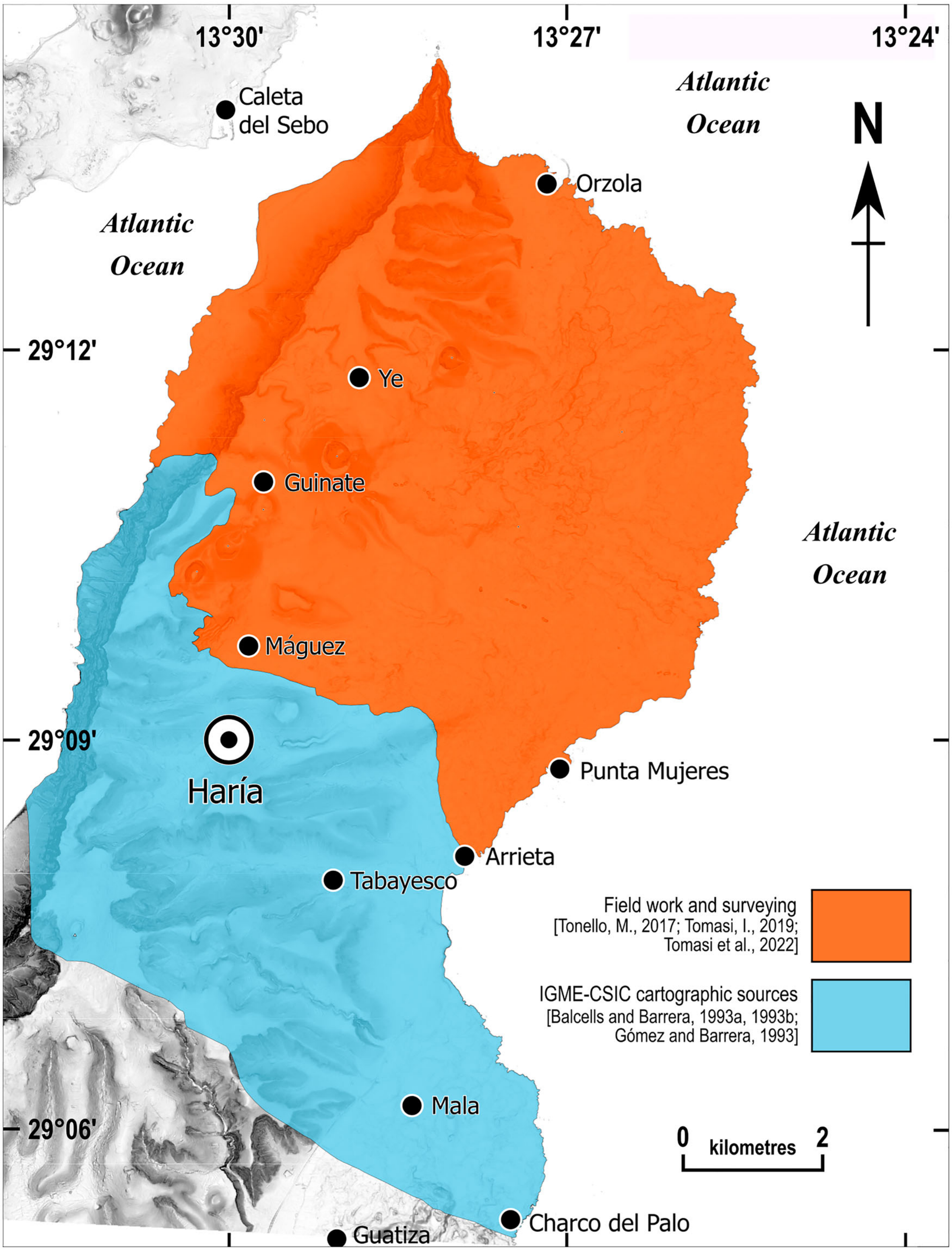

Figure 7. An overview of Lanzarote's northern region, scaled 1:100,000. The tinted portion represents the area of interest addressed by this work. The map lower section was created using 1080-I-IV Balcells and Barrera (1993b); 1080-III Balcells and Barrera (1993a); and 1080-II Gómez and Barrera (1993) as mapping sources, while the upper section is highlighted the area of the map based on field research and several surveys (Tomasi, 2018; Tomasi et al., 2022; Tonello, 2017).

1988; Montoriol-Pous & De Mier, 1969; Tomasi et al., 2022).

Another lava tube, probably of overcrusted origin, is visible on the westward-flowing lava leaked from the Famara cliff (Figure 3(A)). This lava tube is ca. 250 m long and with a diameter of 1–2 m, accessible thanks to the collapse of its ceiling (Figure 5(A), Figure 7(B)). Also in the northern area of the La Corona lava flow, toward Orzola, it is reported a small lava tube with a length of 150 m (Cueva del Lago Né).

3. Methods and material

The cartographic work consisted in the digital mapping of geological units in the municipality of Haría with a focus on volcanic terrains. To this end, we used ArcGIS software to perform the mapping.

The existing geological maps of Lanzarote consist of the 1:100,000 map (Balcells et al., 1994) and seven 1:25.000 maps published by the Spanish Geological Survey (IGME-CSIC). Of these seven maps, three cover the area of interest (Figure 2): 1080-I-IV (*Caleta del Sebo*); 1080-II (*Sòo*) and 1080-III (*Haría*) (Balcells & Barrera, 1993a, 1993b; Gómez & Barrera, 1993). Since 2008, the IGME has systematised the 1:25.000 geological maps in digital format (IGME, 2008). These geological maps have been used as a basis for the southern area of the Main Maphere presented (light-blue in Figure 7).

The field work consisted in the realisation of the geological map based on observations, and using the appropriate symbology by representing the existing stratigraphic units and related geological structures and morphologies. We carried out an extensive field campaign focused on the collection of information about the formation and evolution of the La Corona lava tube system, including the geographical position of the collapses and contact with older units. As noted by previous authors (Hausen, 1959; IGME, 1967a, 1967b; Páez et al., 2002), due to the steepness of the Famara precipices, the delimitation and surface extension of each sequence is not very well defined. The mapping presented in this work (Main Map) related to the Famara cliff relies mostly on remote sensing and several field checks.

We worked in the field mainly using topographic maps (1:10,000), Google Earth satellite images were compiled and plotted over a 5 × 5 m resolution digital terrain model (DTM) downloaded from the Spanish *Centros de Descargas* of the National Geographic Institute (IGN), available at: http://centrodedescargas.cnig.es/CentroDescargas, and by using ArcGIS software. All the elements were mapped using the UTM Zone 28N projection and the REGCAN95 coordinate system.

Terrestrial Laser Scanning (TLS or T-LiDAR) acquisition where used to create a three-dimensional model of the La Corona lava tube (Tomasi et al., 2022) allowing us to accurately identify the morphologies and underground development of the main pyroduct. Since GPS positioning is not possible underground, the position of the lava tube was determined by co-registering the locations of the different collapses in relation to one another.

4. Results

The Main Map presented in this work describes in more detail several items compared to previous maps of the region. In particular, we emphasised the details of:

- the paleosoils and caliche layer interlayered in the Famara sequences;
- the boundaries between the main volcanic complexes and the Series were modified;
- the lava flow fronts and margins of both the La Corona malpaìs and Los Helechos Malpaìs were defined in more detail;
- the distribution of pyroclastic deposits among the lava fields of Los Helechos and La Corona;
- the lava tube path development of the La Corona lava tube system and the location of the entrances of several other lava tubes.

5. Discussion and conclusions

The detailed field work confirmed that the 1:25.000 scale geological maps were not sufficiently detailed to characterise the Pleistocene volcanism as well as to exactly locate the lava tube system of La Corona and its collapses. We decided to produce a unified map (Main Map) of the northern Lanzarote, constrained to the municipality of Haría (107 km^2) as it unifies the area covered by existing maps and it contains all the units of interest discussed above. Additionally, we fixed some ambiguities in the lava flow contacts, in the attribution of lava flow to volcanic vents, and eruption ages in both the printed and digital versions of these previous 1:25.000 scale geological maps (Balcells & Barrera, 1993a, 1993b; Gómez & Barrera, 1993; IGME, 2008).

In this way, we produced a new 1:25.000 scale map for the northernmost region on Lanzarote (orange in Figure 7, Tomasi, 2018; Tomasi et al., 2022; Tonello, 2017).

In this work, we present the first unified map of the northern region of Lanzarote. It integrates all volcanic forms, including vents, lava flows, tephra cones, pyroclastic deposits, dikes, lava tubes, etc. This map is produced in A0 format, and integrates field survey observations with several maps of Lanzarote at different scales, from 1:100,000–1:25.000. The Main Map is accompanied by two cross-sections showing the Pleistocene volcanic alignment of Los Helechos-La Corona-La Quemada, from south-west towards north-east (I-I') and the deployment of the lava tube system of La Corona towards east (II-II'). A simplified geological map of Lanzarote shows the location of the IGME maps. This work may serve as a useful contribution to consolidate and highlight knowledge of the northern region of the island.

Software

Digitalisation and geo-referencing of the map elements was made using ERSI© ArcGIS Pro 2.9. The final map layout and pictures were produced using Inkscape 0.92.4.

Geological information

The Main Map presented in this work corresponds to the municipality of Haría, covering an area of 106.59 km^2. The area is delimited by the coordinates 13°32’W–13°24’W, 29°05’N–29°14’N (REGCAN95).

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Disclosure statement

No potential conflict of interest was reported by the author (s).

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Data availability statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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