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ORIGIN AND EVOLUTION OF AN INFLATED LAVA TUBE BETWEEN THE MIO-PLIOCENE VOLCANIC COMPLEX OF FAMARA AND THE QUATERNARY LAVA FLOWS OF LA CORONA IN LANZAROTE (CANARY ISLANDS)

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INDICE

INDICE 4

ABSTRACT 6

RIASSUNTO 8

INTRODUCTION 10

CHAPTER 1: GEOLOGICAL SETTING 12

  1.1 EVOLUTION AND AGE OF THE CANARY ISLANDS 12

    1.1.1 SUBAERIAL ISLAND AGES AND HOT SPOT MODEL 13

    1.1.2 A UNIFYING MODEL 15

    1.1.3 SEAMOUNT AGES AND A NEW MODEL 16

  1.2 LANZAROTE 21

CHAPTER 2: LAVA TUBES 30

  2.1 CLASSIFICATION 31

    2.1.1 FORMING PROCESSES 31

  2.2 MORPHOLOGIES 39

    2.2.1 OUTER FEAUTURES 40

    2.2.2 INNER FEATURES 41

CHAPTER 3: METHODS 50

  3.1 SATELLITE-BASED REMOTE SENSING 50

  3.2 DRONE PHOTOGRAMMETRY 52

  3.3 LASER SCANNING 59

CHAPTER 4: FIELDWORK ACTIVITY 62

  4.1 OUTDOOR FIELDWORK 62

    4.1.1 THE FAMARA COMPLEX 62

    4.1.2 LAPILLI LAYER 72

    4.1.3 QUATERNARY VOLCANIC COMPLEX 81

  4.2 CAVE-IN FIELDWORK 85

    4.2.1 LAVA TUBE MORFOLOGY 95

  4.3 DESCRIPTION OF THE GEOLOGICAL MAP 97

CHAPTER 5: RESULTS AND DISCUSSION 100

  5.1 THE FAMARA COMPLEX 100

  5.2 THE QUATERNARY VOLCANISM 101

  5.3 LAVA TUBE ORIGIN AND EVOLUTION 103

CHAPTER 6: CONCLUSIONS 106

REFERENCES 108
WEBOGRAPHY...110

ABSTRACT

The island of Lanzarote (Canary Islands) has a volcanic origin and among the volcanic landforms existing in Lanzarote, some of them are peculiar both of Earth and Mars, such as shield-volcanoes, cinder cones, tuff rings and lava tubes, making Lanzarote a good Martian analogous. In particular, the study of lava tubes has covered great importance in the space research in the last years because they represent the ideal environment to host life-forms on Mars and an important factor for the habitability not only of Mars but also of the Moon.

The northern part of the island has been affected by two periods of volcanic activity: the first one, long-lasting that built up the Famara complex among the Miocene and Pliocene and the second, short-lived but intense that formed the NE-SW alignment of volcanic cones of Los Helechos – La Corona – La Quemada during the Quaternary.

The Famara complex is the remnant of a shield-volcano rose up in three different stages, separated by periods of inactivity or erosional gaps. The lower unit (10.2-8.3 Ma) is made of essentially basaltic lava flows, the intermediate unit (6.7-5.3 Ma) is represented by pyroclastic deposits, both scoria cones and fallout material and the upper unit (3.8-3.9 Ma) is formed of basaltic lava flows filling in the ravines gouged out in the period of quiescence between the intermediate and the upper unit.

These three units are separated from each other by soils and/or sedimentary beds formed during the gap periods between the different phases of activity but we have been able to recognize and describe other six soils interlayered among the lava flows of the third unit.

The Quaternary volcanism occurred with fissure eruptions giving rise to three volcanic edifices that, with their basaltic lava flows, buried the reshaped and partially eroded massif of Famara, covering the central and eastern portions on an area of almost 50 km^2.

The most interesting feature of this part of Lanzarote is the presence of the 7.6 km long lava tube of La Corona and we have suggested that it has formed between the Famara complex and La Corona lava flows. These lava flows, through the inflation mechanism, have formed the lava tube by exploiting a discontinuity provided by a widespread level of dark lapilli, since it has provided a weakening zone that eased the placement of the lava tube.

RIASSUNTO

L’isola di Lanzarote (Isole Canarie) è di origine vulcanica e tra le forme vulcaniche presenti, alcune di esse sono peculiari sia della Terra che di Marte, come i vulcani a scudo, i coni di cenere, i tuff rings e i tubi lavici, rendendo Lanzarote un buon analogo marziano. In particolare lo studio dei tubi lavici è stato di grande importanza nelle ricerche spaziali degli ultimi anni in quanto essi rappresentano l’ambiente ideale per ospitare forme di vita su Marte e un importante fattore di abitabilità non solo di Marte ma anche della Luna.

La parte settentrionale dell’isola è stata interessata da due periodi di attività vulcanica: il primo e più duraturo che formò il complesso di Famara tra il Miocene e il Pliocene e il secondo, più breve ma intenso che formò l’allineamento vulcanico Los Helechos – La Corona – La Quemada, orientato NE-SO, durante il Quaternario.

Il complesso di Famara è ciò che rimane di un vulcano a scudo formatosi per mezzo di tre differenti fasi di attività separate da periodi di inattività o di erosione. L’unità inferiore (10.2-8.3 Ma) è costituita essenzialmente da colate basaltiche, l’unità intermedia (6.7-5.3 Ma) è rappresentata da depositi piroclastici sia costituenti dei coni di scorie che di caduta, mentre l’unità superiore (3.8-3.9 Ma) è formata da colate basaltiche che hanno riempito valli e depressioni originatesi durante il periodo di inattività tra la fase intermedia e quella superiore.

Queste tre unità sono separate l’una dall’altra da suoli e/o formazioni sedimentarie che si sono formati durante i periodi di quiescenza tra una fase di attività e l’altra, ma noi siamo stati in grado di riconoscere e descrivere altri sei suoli tra le colate basaltiche dell’unità superiore.

Il vulcanesimo Quaternario si manifestò con un’eruzione di tipo fissurale dando origine a tre edifici vulcanici che, con le relative colate, seppellirono il massiccio di Famara ormai rimodellato dall’erosione, coprendo le sue porzioni centrale ed orientale su un’area di quasi 50 km^2.

La caratteristica più importante di questa zona di Lanzarote è la presenza del tubo lavico de La Corona lungo 7.6 km e noi abbiamo suggerito che esso si sia formato tra il complesso di Famara e le colate de La Corona. Queste colate, attraverso il meccanismo dell’inflation, hanno dato origine al tubo lavico sfruttando una discontinuità rappresentata da un esteso livello di lapilli neri, dal momento che essi costituiscono una zona di debolezza che ha facilitato la formazione del tubo lavico.

INTRODUCTION

Figure. The Canary Islands.

Lanzarote is the north-easternmost island of the Canaries and, as the other islands of the archipelago, has a volcanic origin. Among the volcanic forms existing in Lanzarote, some of them are peculiar both of Earth and Mars, such as shield-volcanoes, cinder cones, tuff rings and lava tubes, and in particular the latter have covered great importance in the space research in the last years because they represent the ideal environment to host life-forms on Mars and an important factor for the habitability not only of Mars but also of the Moon. In fact, inside the lava tubes there aren’t the large temperature ranges that characterise the Martian and lunar surface and they provide a shield for the solar radiations as well as a protection for the impacts of micrometeorites (Blair et al., 2017).

The combination between the overall presence of volcanic forms and the aridity of the landscape, make Lanzarote a good Martian analogous. For this reason, the European Space Agency (ESA) has recently identified Lanzarote as a good and suitable place for the geologic training of astronauts.

First of all, it is essential to have a complete understanding of the lava tubes through the study of their processes of formation and evolution and the description of the geological setting through which they develop.

In order to do this, we have studied the northernmost area of Lanzarote that is dominated by the Famara massif (the remnant of a shield volcano) and the overprinted volcanoes Los Helechos, La Quemada and La Corona. The latter is particularly important because it has been the responsible for the formation of about 7,6 km long lava tube (with the last 1,6 km of submerged portion) and of an extensive lava field called in Spanish language “Malpaís de La Corona”.

To reconstruct the geological history of this area, we have realised a geologic map for two different purposes: 1) to better identify the different volcanic stages of the Famara complex interlayered by erosive gaps, soils formations and/or sedimentary deposits and 2) to understand the relationships between this complex and the abovementioned volcanic group of Los Helechos - La Quemada - La Corona, not only by the walk-over survey, but also by remote sensing methods. For this purpose, the field survey has been coupled with drone-photogrammetric surveys and the study of the lava tube of La Corona has been carried out both by walk-over and laser scanning survey. The remote sensing analysis played an important role to clarify the relations between different lava flows either of different volcanic events or of the same event.

CHAPTER 1: GEOLOGICAL SETTING

The Canary Island Seamount Province (CISP) forms a scattered hotspot track on the Atlantic ocean floor, parallel to the northwestern African continental margin and covers an area of 1300 km in length and 350 km in width.

This volcanic province comprises more than 100 seamounts, isolated volcanic structures on the seafloor ranging from small (less than 1000 m height) to mid-sized (more than 1000 m) and mid-sized explosive (less than 700 m water depth) to ocean islands.

The archipelago includes seven main islands such as, from east to the west, Lanzarote, Fuerteventura, Gran Canaria, Tenerife, La Gomera, La Palma and El Hierro and other several islets extending for about 500 km nearly in E-W direction. The Canary Islands lie on the very slow African plate that is moving at a speed of 2 cm/a (van der Bogaard, 2013) and developed in a geodynamic setting characterized by Jurassic oceanic lithosphere formed during the first stage of opening of the Atlantic ocean. The study of the magnetic anomalies shows that the ages of the oceanic crust beneath Canaries range between 156 and 175 Ma, as demonstrated by the M25 magnetic anomaly near La Palma and El Hierro and the S1 magnetic anomaly situated between the Lanzarote-Fuerteventura ridge and the African continent respectively (Dañobeitia and Canales, 2000). Because of the proximity of the archipelago to the African coasts (Fuerteventura is less than 100 km off the Moroccan coasts), the easternmost islands like Lanzarote and Fuerteventura, rest on a lithosphere that is transitional between continent and ocean.

1.1 EVOLUTION AND AGE OF THE CANARY ISLANDS

The volcanic activity of the Canaries has not been continuous through time, as shown by the complete stratigraphic sections recognized throughout the islands. These sections consist of four parts: 1) a basal complex (*pre-shield* stage or seamount series), which is the submarine part of the sequence composed of turbiditic sediments intruded by sheeted dike swarms and by plutons, 2) a *shield-building* stage in which the rapid growth of shield-volcanoes occurs, 3) a period of quiescence and deep erosion (*erosion gap*) and finally 4) a *post-erosional* stage of activity.

In the older islands of the archipelago, this complete sequence is better exposed than the younger ones, because the latter have not still reached the final stages.

1.1.1 SUBAERIAL ISLAND AGES AND HOT SPOT MODEL

Extensive K/Ar dating of previously defined magnetostratigraphic units, carried out in the Canaries (Carracedo et al., 1998).

The ages of the oldest subaerial volcanic rocks are of 20.6 Ma in Fuerteventura, 15.5 Ma in Lanzarote, 14.5 Ma in Gran Canaria, 12 Ma in La Gomera, 7.5 Ma in Tenerife, 2 Ma in La Palma and 1.12 in El Hierro. Also the dating of the periods without extrusive activity (erosion gap) results important and they are of two million years (from 12 to 10 Ma) in Lanzarote, three million years (from 3 to 0 Ma) in La Gomera, five million years (from 10 to 5 Ma) in Gran Canaria and seven million years (from 12 to 5 Ma) in Fuerteventura.

From these results, it appears that the eruptive gaps occur only in the early-emerged islands of Lanzarote, Fuerteventura, Gran Canaria and La Gomera, on the other hand, the volcanic activity has continued uninterrupted from the time of subaerial emergence to the present day in the late-emerged islands of Tenerife, La Palma and El Hierro. So, it is clear that the older islands of Lanzarote, Fuerteventura and Gran Canaria are nowadays at post-erosional stage volcanism, the island of La Gomera is presently in the gap stage and the younger islands of Tenerife, El Hierro and La Palma are in the pre-gap shield-building stage, with Tenerife approaching the period of quiescence while La Palma and El Hierro are in the most active phase of shield-stage.

As a result, every comparable unit (the basal complexes, the shield volcanoes, or the post-shield phases) is older in the eastern islands than in the western ones.

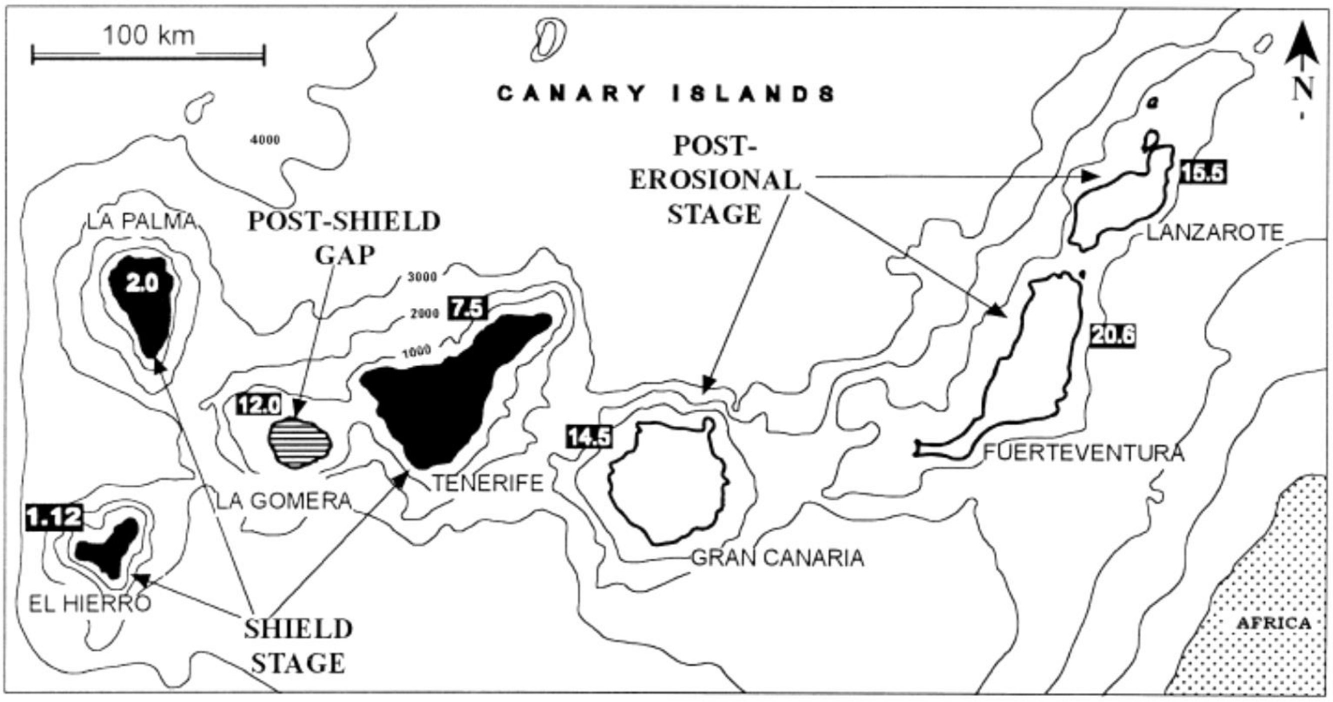

Figure 1.1. Oldest published K–Ar ages of the subaerial volcanism of the Canary Islands. In this figure, the islands in the shield-stage of development, in the gap stage and in the post-erosional stage are shown (Carracedo et al., 1998).

Figure 1.1 shows a rough decreasing of the ages from NE to SW, as occurs typically on the hotspot-related islands group.

To support the hotspot model, Carracedo et al. (1998) compared the Canary Islands with the Hawaiian Islands, the prototypical hotspot-related islands group. They noticed some differences between the two islands groups affecting the lithospheric swell, age vs. distance correlation, subsidence rate, magmas composition, period of quiescence and lasting of volcanic activity for single islands.

Even though the differences between Canaries and Hawaii are substantial, Carracedo et al. (1998) suggested that these differences are due to the divergence on the velocity of the African and Pacific plates and on the age of the Atlantic and Pacific oceanic crust. Indeed, the Pacific plate is faster than African one (10 cm/a against 1.9 cm/a) and the oceanic crust beneath Canaries is older than that beneath Hawaii.

The characteristics of the Canary Islands are however more similar to those of another hotspot-related islands group lying on a slow-moving plate: Cape Verde. It is just the slow speed of the African plate that has led to consider Canaries and Cape Verde among the best analogous for Martian volcanism, being Mars a one shell planet.

1.1.2 A UNIFYING MODEL

The Canarian Archipelago is located adjacent to a region of intense active deformation, comprising the Atlas Mountains, Rif Mountains, Alboran Sea and Baetic Cordillera provinces of the Alpine orogenic belt. Hence, there might be a structural control on the activity of the supposed hotspot. The correlation among these two areas, shows the same types of structures such as transcurrent faults having not only the same set of strikes (NE, NW and N-S), but also the same behaviour, left- and right-handed. Those common features indicate that both in the Canaries and Atlas Mountains the same stress field works.

The discontinuous volcanic activity of the Canaries with long periods of quiescence in fact, is typical of a tectonic-controlled volcanism because it might depend on changes in the lithosphere stress regime. For this reason, Anguita and Hernán (2000) proposed a model for the origin of the volcanism in the Canary Islands, suggesting a strong interaction between the mantle plume and the tectonic setting on which the archipelago formed.

According to Hoernle et al. (1995) that stated the presence of a large-scale mantle upwelling beneath the eastern Atlantic, western and central Europe, Anguita & Hernán (2000) proposed that it might be the remnant of a fossil plume arrived in the upper mantle at the end of Triassic (200 Ma ca.), feeding the Central Atlantic Magmatic Province and accompanying the opening of central Atlantic.

The magmatism in the Canaries occurred where and when an efficient fractures system, inherited from the Mesozoic failed arm rift, provided a pathway for the rising of the magma from this upwelling region. In particular, during the tensional periods the fractures would serve as conduits for the magma while in the compressive phases they would cause the uplift of the islands as sets of flower structures (Anguita and Hernán, 2000).

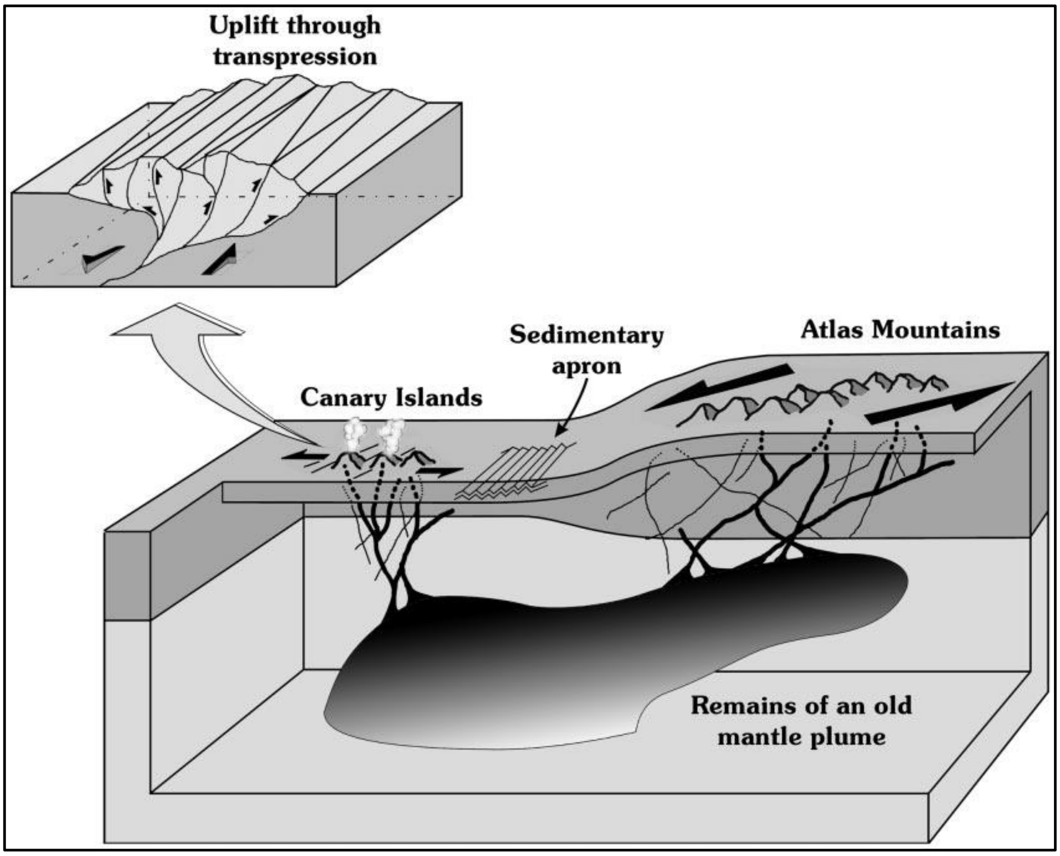

Figure 1.2. Cartoon illustrating the unifying hypothesis on the origin of the Canary Islands. The inset represents a transpressive phase, when the islands would emerge as flower structures (Anguita & Hernán, 2000).

The main obstacle for the acceptance of this model has been the lack of continuous faults connecting Canaries and Atlas Mountains. The plot of all seismic events in the zone permits the identification of a seismic gap between the islands and the High Atlas chain: this seismic gap is also consistent with the absence of volcanic constructs in this area, which could be explained as due to the lack of faults that could tap the thermal anomaly.

1.1.3 SEAMOUNT AGES AND A NEW MODEL

Van der Bogaard (2013) provided new ^{40}Ar/^{39}Ar ages of the seamounts of the CISP, showing that they do not grow systematically older from the southwest (Tropic, 119 Ma) to the northeast (Essaouira, 68 Ma) and that the ages vary from 133 Ma to 0.2 Ma in the central archipelago and from 142 Ma to 91 Ma in the southwest.

These values nominate the Canary Island Seamount Province as oldest hotspot track in the Atlantic Ocean, and most long-lived preserved on Earth.

By comparing the ages of the oldest subaerial volcanic rocks provided by Carracedo et al. (1998) with this new dating, it appears that there are Miocene to Pleistocene islands in the middle of Cretaceous seamount field (fig. 1.3): this may be due to the fact that only the subaerial island tips of these giant seamounts are young but their seamount roots are Early Cretaceous or older.

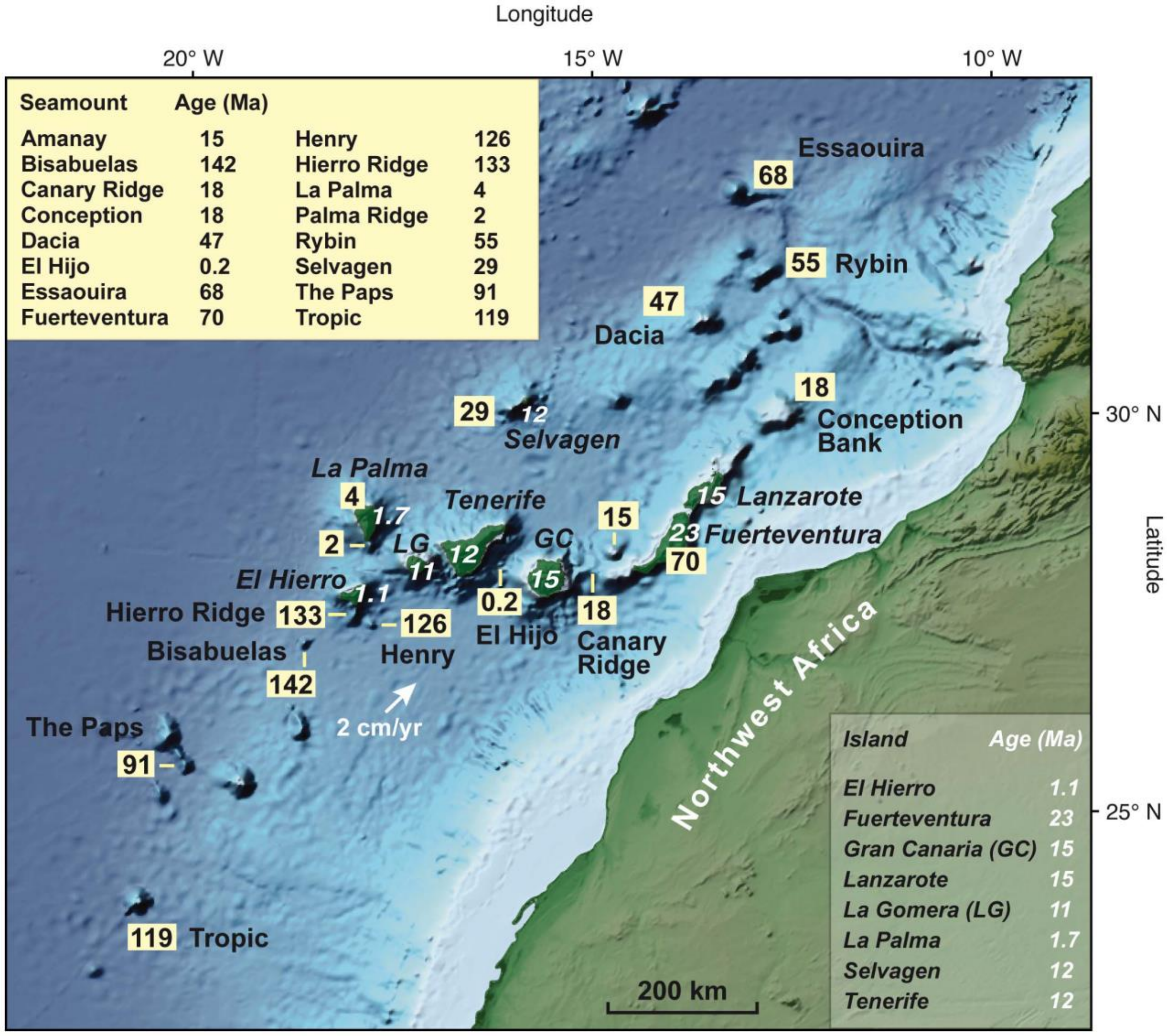

Figure 1.3. Topographic map of the NW African continental margin and age distribution in the Canary Island Seamount Province (CISP). Numbers are the oldest ages determined for seamounts and islands in millions of years. Oldest subaerial island ages are in white (van der Bogaard, 2013).

From this confront, it is also clear that there is absolutely no correlation between ages and distances from the supposed hot spot, as occurs, for example, for the Hawaii Archipelago, and for this reason the temporal and spatial distribution of Canary seamounts is irreconcilable with single fixed-plume models.

On the other hand, shallow passive mantle upwelling beneath mid-ocean ridges can explain the origin of diffuse seamount chains but only in young ocean basins when seamount formation closely follows the mid-ocean ridge. Hence, an origin of the entire CISP from passive mantle upwelling beneath the mid-Atlantic ridge is not reasonable because it does not explain the more recent volcanic activity in the Canaries.

According to van der Bogaard (2013), only shallow mantle convection at the rifted continental lithosphere flanks can explain the alignment, age distribution, plate tectonic setting and long history of individual centres of the CISP, and agrees with the observed mix of geochemical mantle components. Breakup of the Pangaean continent exposed the thick cratonic lithosphere to hot asthenospheric mantle and caused mantle upwelling (edge-driven convection) and recycling of subcontinental lithosphere.

This author concludes that plate-bound shallow mantle convection is an important mechanism of seamount formation in young ocean basins bordered by rifted continental margins and is capable of sustaining extremely long-lived hotspot tracks for at least 142 Ma in case of the Canary Island Seamount Province.

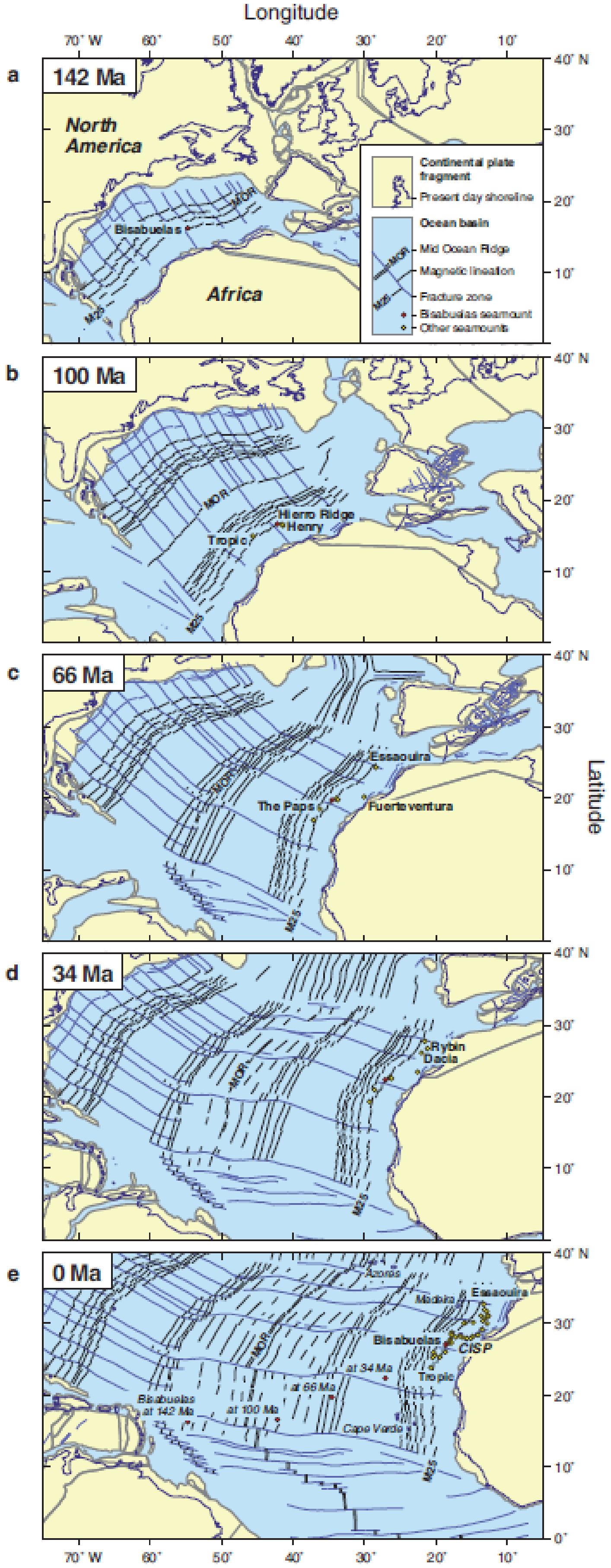

Figure 1.4. Plate tectonic reconstruction and setting of CISP seamounts at 142 Ma (a), 100 Ma (b), 66 Ma (c, K-Pg boundary), 34 Ma (d), and Present (e).

1.2 LANZAROTE

Lanzarote is located at the north-eastern part of the Canarian Archipelago, more than 100 km from the coast of Morocco and, with a surface area of 846 km^2, is the fourth largest of the islands (11% of the regional surface area). This island has the lowest peaks of the archipelago, reaching an altitude of a mere 671 m at *Las Peñas del Chache*, in the Famara massif. The fact that this is a low-lying island, in comparison with the other Canaries, is not only due to a lesser growth of the original volcanic structures but it is a consequence of the time, indeed, being Lanzarote the one of the oldest islands (15.5 Ma), the erosion has had millions of years to mould the surface.

Lanzarote is not a single block like the other Canary Islands but, with Fuerteventura, forms a single enormous volcanic complex, since the depth of the sea between the two islands, La Bocaina strait, reaches only 40 metres.

The Lanzarote-Fuerteventura ridge, runs NNE to SSW (35º N) along a supposed fracture alignment parallel to the African coast coincident with the continental-oceanic crust transition whose weakness favours the ascent of magma bodies.

The geological evolution of the island and its different volcanic phases have been constrained by Carracedo and Rodriguez Badiola (1993), by measuring the magnetic polarity impressed in the lavas and combining it with the radiometric dating.

The first stage of activity was submarine volcanism. Piles of submarine pyroclasts and lavas (pillow-lavas and hyaloclastites), since the Middle Oligocene between 35 and 28 Ma, started to cover the submarine sediments (limestone, marls, clays, etc.) from a depth of 2598 metres. This activity must have been located in what is now the centre-south of Lanzarote and it was the only underwater activity of the history of the island. There no signs of it anywhere on the island today, but it constitutes only the basement on which the island rests.

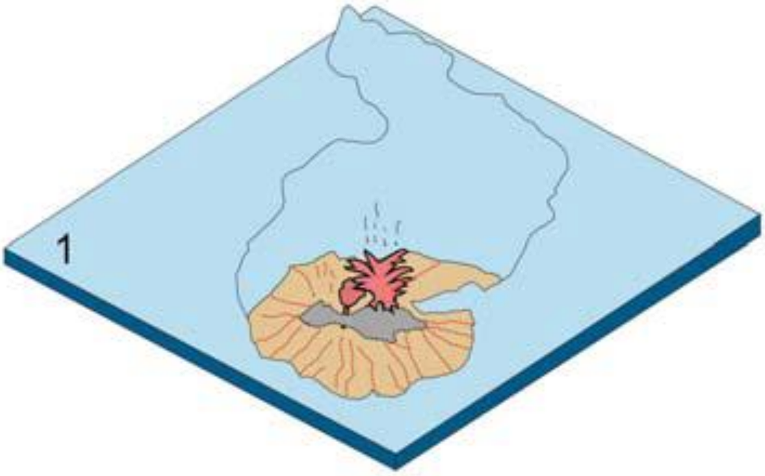

Figure 1.5. Volcanological evolution of Lanzarote. The picture shows the formation of the massif of Los Ajaches (Hansen and Perez Torrado, 2005).

After a long period of quiescence, the volcanic activity started up again, between 14.5 and 13.5 Ma, giving rise to the Los Ajaches edifice in the south of the island (fig. 1.5). During this event, very large volumes of lava formed a shield-type volcanic edifice without any discordances: in fact, this edifice was built up during a single episode lasting 1 Ma.

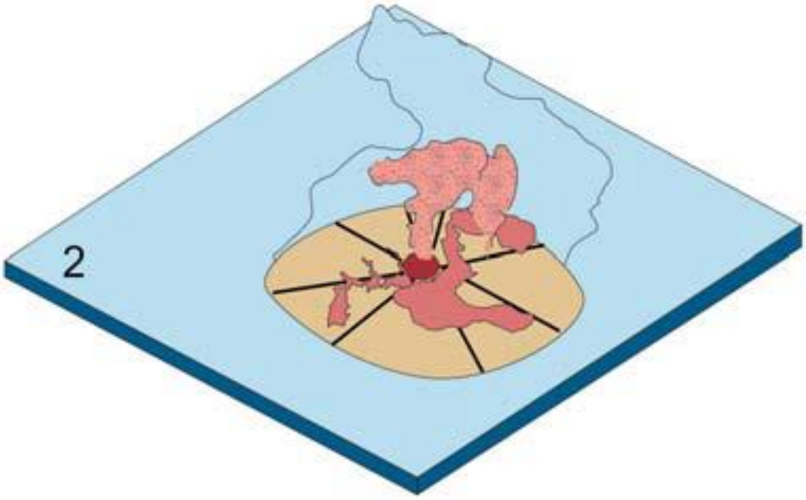

Figure 1.6. Volcanological evolution of Lanzarote. The picture shows erosion acting on the massif of Los Ajaches (Hansen and Perez Torrado, 2005).

Three million years passed with no eruptive activity, during which the island started to be eroded away (fig. 1.6).

The volcanic activity took up about 10.2 Ma at the north of Lanzarote, on the area now covered by the Famara Massif (fig. 1.7).

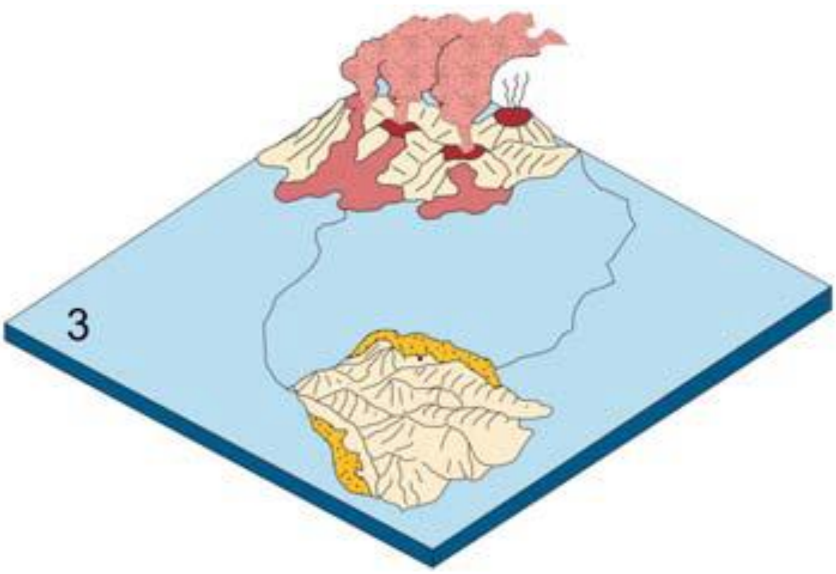

Figure 1.7. Volcanological evolution of Lanzarote. The figure displays the formation of the Famara massif (Hansen and Perez Torrado, 2005).

In the Canary Islands, the term “volcanic massif” is used for topographical features that, after becoming complex rifts, shield or strato-volcanoes, have been transformed by erosion into declining forms in which the original structures have almost completely disappeared (only the piles and intrusions remain as such).

Unlike Los Ajaches, the volcanic structure of Famara was constructed in three stages separated by erosive gaps, which can be distinguished in the current scarps of the massif by the presence of ancient soils and/or erosion areas. The temporary breaks of the volcanic activity favoured the formation of sedimentary deposits made of conglomerates, marine sandstones and fluvial-aeolian sands; some of these are fossil-bearing (Lomoschitz et al., 2016).

The lower unit is formed by an accumulation of very thick basalt lava flows expelled between 10.2 and 8.3 Ma. In the intermediate unit, there are frequently cones and mantles of pyroclasts erupted between 6.7 and 5.3 Ma. The upper unit was emitted from 3.9 to 3.8 Ma and it is comprised of very powerful basalt extrusions that filled in the ravines gouged out in the period of eruptive quiescence between the intermediate and the upper unit. The resulting structure would have been a mega ridge-type volcanic edifice.

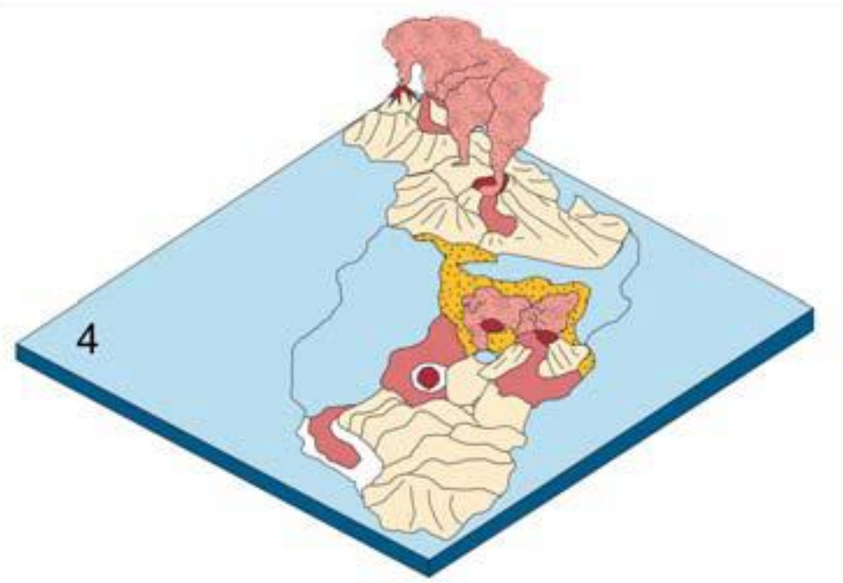

Figure 1.8. Volcanological evolution of Lanzarote. The figure shows the Tias volcanism (Hansen and Perez Torrado, 2005).

At the same time as the intermediate stage of Famara, volcanism appeared in the area that is now the village of Tias, at present central-southern part of the island (fig. 1.8). Around this area, there are remains of lava flows and basalt emission centres that are of 6.1 Ma and along the northern edge of Los Ajaches massif there are lavas of the “Tias volcanism” of 6.6 Ma. Although any large edifice was built, these emissions occurred in the gap between the already formed islands of Famara and Los Ajaches, creating the first land bridge between the two. The phases described above constitute the Series I or the First Cycle of sub-aerial volcanic activity.

At the end of the Tias Volcanism and after the Famara activity stopped, a period of erosive decline began and lasted at least 2.5 million years. Famara ridge was quickly reduced in size by the abrasive action of the sea and by supposed gigantic landslides down to the west with the consequent formation of a massive cliff (fig. 1.9).

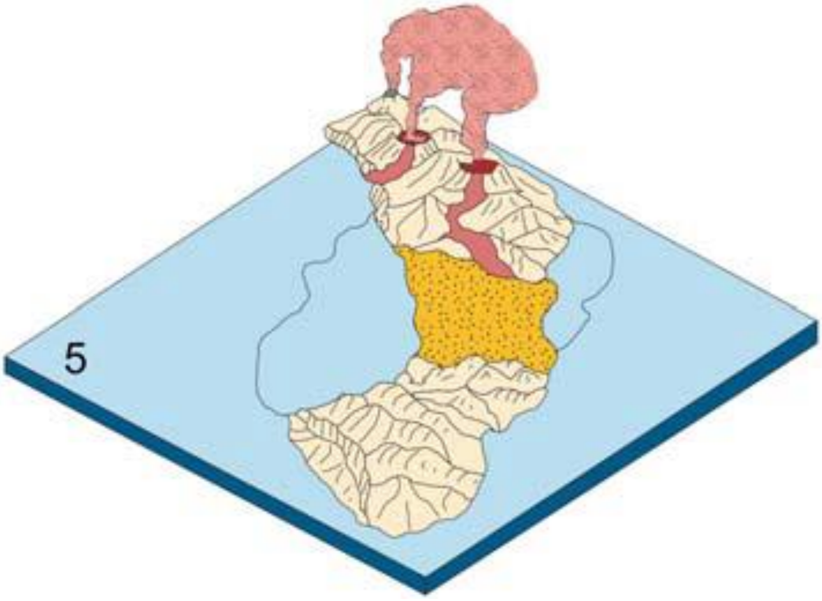

Figure 1.9. Volcanological evolution of Lanzarote. The picture represents the erosive phase acting on the Famara massif (Hansen and Perez Torrado, 2005).

From the Lower Quaternary Period, the volcanic activity entered the Series II or the Second Cycle of eruptions with emission centres above all on the peripheral edges of the massifs of Famara and Los Ajaches (fig. 1.10).

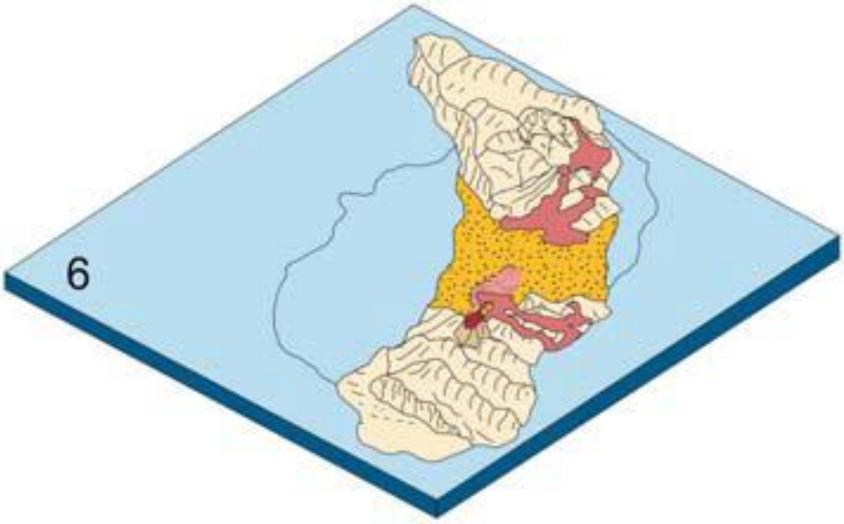

Figure 1.10. Volcanological evolution of Lanzarote. The figure displays the volcanic activity on the peripheral edges of the massifs of Famara and Los Ajaches (Hansen and Perez Torrado, 2005).

Over the last 700.000 years, volcanism has shifted especially between the two former massifs and has become more fissural in nature creating a chain of emission centres running NE-SW (fig. 1.11). This phase corresponds to the Series III.

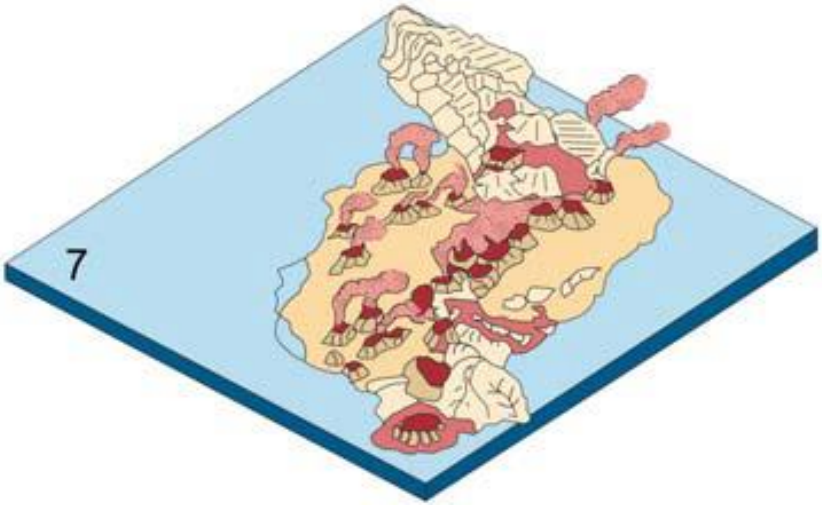

Figure 1.11. Volcanological evolution of Lanzarote. The figure shows the volcanic alignments of the Series III between the massifs of Famara and Los Ajaches (Hansen and Perez Torrado, 2005).

The Serie IV of activity has started with some fissure eruptions occurred on the pre-existing Famara massif following the same NE-SW trend, giving rise to the volcanic alignment of Los Helechos-La Corona-La Quemada (fig. 1.12).

Figure 1.12. Volcanological evolution of Lanzarote. The picture represents the Series IV of activity (Hansen and Perez Torrado, 2005).

The oldest edifice is La Quemada followed by the eruptions of Los Helechos around 91 Ka ago while La Corona erupted during the last ice age around 21,6 Ka ago.
The $^{40}Ar/^{39}Ar$ age for the lavas of La Corona, gives a mean of 21 ± 6.5 Ka and agrees with the geological observation and the study of the lava tube associated with this edifice (Carracedo et al., 2003). This lava tube terminates 1.6 km beyond the actual coastline at a depth of 80 metres under the sea level, but it could not have reached

that depth through an underwater medium: in fact, between 18 and 21 Ka, during the last ice age, the sea level reached his minimum by allowing lava tube to form on a wide area that is now submerged.

The activity of this group of volcanoes, as we will see later, transformed considerably the paleogeography of the northern part of the Famara Massif modifying the drainage network, filling in the bottom and valleys with their lavas and pyroclasts and burying its former eastern cliff, covering an area of almost 50 km^2.

The volcanic activity of the Series IV continued with the so-called historic eruptions of 1730 - 1736 and of 1824, following the same NE-SW fissural fashion (fig. 1.13).

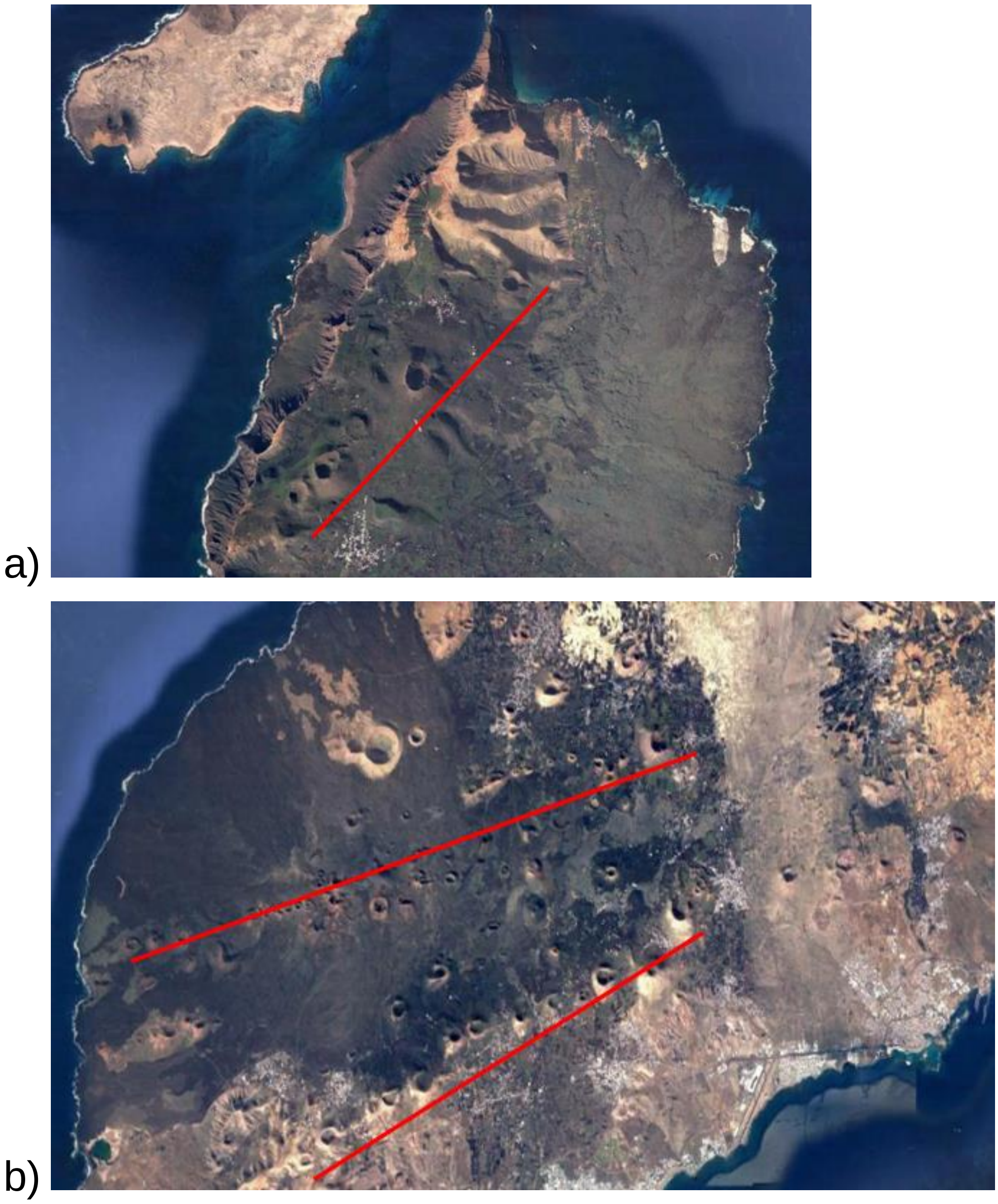

Figure 1.13. (a) Satellite view of the north of Lanzarote showing the Famara massif with the overprinted volcanic group of Los Helechos - La Corona – La Quemada. (b) Satellite view of the central-southern part of Lanzarote showing the volcanic edifices of the historic eruptions. The red lines highlight the quaternary NE-SW volcanic alignments.

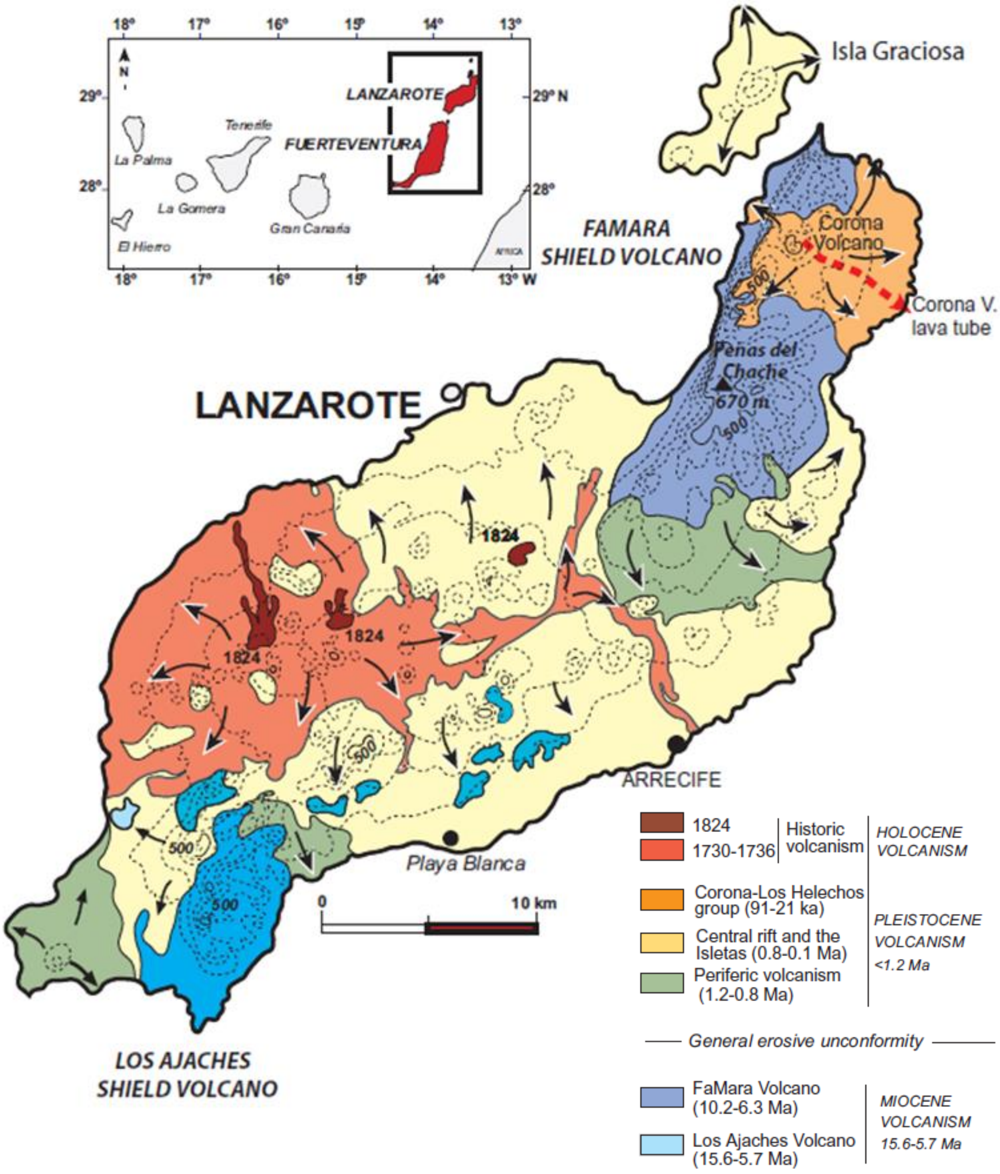

Figure 1.14. Geological Map of Lanzarote from Hoernle and Carracedo (2009).

CHAPTER 2: LAVA TUBES

Lava tubes are underground conducts formed by lava flows, recognisable in plan view as depressed or overpressed elongated areas with sinuous path and constitute one of the most characteristic forms of the volcanic environments (De Berardinis, 2013). Their formation requires a period of time that may vary from a week to some months (Calvari and Pinkerton, 1998) and starts next to a vent, where there is a greater supply of lava; from here, lava flows spread for long distances and if the condition of viscosity, flow rate and topography are advantageous, a complex network of caves and tunnels may develop. It is possible to date their formation exactly, since the age of the eruption that has given rise to the flow in which they have developed is known. This characteristic is fundamental to distinguish them from karstic caves in calcareous rock, whose formation is the result of chemical and physical action of excavation of the rock that may last for hundreds of thousands or even millions of years (Calvari and Puglisi, 2007).

But the formation of a tube obviously required its emptying by lava flows. In fact, once effusion rate decreases, lava can be drained leaving empty galleries (Calvari and Pinkerton, 1998). The cause of the drainage may be the downstream slope of the tunnel, that permit to the flow to continue after the ending of the supply (De Berardinis, 2013).

The network of tubes that can be formed, along with eventual ephemeral vents and secondary flows, is responsible for most of the widening, thickening and lengthening of a lava flow, as suggest the observations of Calvari and Pinkerton (1998) of the Etna’s 1991-93 eruptions: the resulting network of lava tubes permitted the formation of a flow field that was considerably more extensive than would have been possible if all the flows had been channel-fed.

In particular, considering individual flows instead of total flow field parameters, these authors demonstrated that the maximum flow length is related to the mean discharge rate, ground slope and emplacement duration. To give an idea of such distances, some lavas can flow over tens and sometimes hundreds of km in presence of a lava tubes (below a roof that grows downward from the fast cooling crust) because in this way cooling is greatly retarded (Schminke, 2004). Observations by Hawaiian Volcano Observatory, found temperature drops of only 6 to 16 degrees Celcius in distances up to 14 km in active tubes.

On the Earth the longest surveyed uninterrupted lava tube is the 65.5 km long Kazumura Cave on the Hawaiian Kilauea Volcano and the longest duct-supported flow is the 160 km long Undara flow in Australia.

2.1 CLASSIFICATION

The lava tubes can be classified at least in two ways taking into account the morphologies of the tunnels system and the type of forming processes of this volcanic caves.

From a morphological point of view, there are three types of lava tubes: single-trunked systems, double (or multiple)-trunked systems and superimposed-trunked systems (Kempe, 2012).

The **single-trunked systems** comprise the most of the documented lava tubes and they are constituted by a single tunnel fed by one vent.

The **double-trunked systems** are comprised of two lava tunnels active side by side at the same time and fed by two separate eruption points. Such tunnels can interact and cause more complex morphologies than previous type.

The **superimposed-trunked systems** are the least understood and documented. They are defined as a set of lava tunnels superimposing and crossing each other with connecting openings between the levels that serve for eventual exchanges of lava. The tubes are active at the same time but the upper tunnels stop their activity first. Such systems could arise when a volcanic vent increases its output volume during an ongoing eruption, thus the already established pyroducts cannot accommodate the increased flow volume and a new level of independently operating tunnels is built on top of the already active ones.

2.1.1 FORMING PROCESSES

The classification of lava tubes on the basis of their forming process and the real comprehension of the mechanisms, has required observations for a long time, not only from outside but mainly from the inside.

Originally described from Iceland, lava tubes were observed actively forming in Hawaii during the 19th century but the exploration of volcanic rock caves, termed vulcanospeleology by William R. Halliday, did not receive much attention until the

1970s; since then, hundreds of caves from all over the world have been explored and surveyed to gain an insight into the formation and evolution of pyroducts from the inside (Kempe, 2010; Kempe, 2012).

The formation of lava tubes occurs in volcanic areas characterised by effusive activity on which magmas of basaltic composition are involved. In fact, the basaltic lava flows have low viscosity and high temperatures that allow them to have a considerable erosive power and to spread over wide areas with thicknesses from centimetres to metres (De Berardinis, 2013).

The more explosive type of eruption, where rocks, cinders and ashes are ejected and whole tops of volcanoes may be blown off, do not typically form tubes.

Once basaltic lava flow is effused, it starts to cool and develop a glassy crust whose exterior look permit a distinction between two types of flows: pahoehoe and aa flows. These are Hawaiian words that have been adopted by geologists working in other basaltic areas besides Hawaii.

The **pahoehoe**-type flows have lower viscosity and velocity than aa-type and are commonly bulbous with a smooth skin. It happens that this thin outer glassy film breaks off quickly and is removed rapidly by wind and rain. Pahoehoe lavas commonly move as thin flow units because of their low viscosity and such stacking and interfingering units cool together to form complex lava flows. As a result of the plastic behaviour of the crust and of the continuous lava flowing beneath the crust, on the surface can develop series of wrinkles that impart to the crust a typical *ropy* texture.

Figure 2.1. Ropy pahoehoe lava on the south flank of Kilauea volcano, Hawaii (Schminke, 2004).

The **aa**-type flows have a greater amount in volatiles than pahoehoe and this cause a degassing favouring the early crystallization of the crust that breaks down as the underlying lava flows. The aa flows commonly have a higher viscosity and shear strain than the pahoehoe-type.

This type of lava is characterized by very rough and fractured top surface with the loose fragments that may be spinose (clinkers) or more rarely smooth (blocks) and that have been pushed upward. In cross section, aa lava flows but also the pahoehoe-type consist of three parts: a basal breccia, a more massive central part, and a capping breccia. Observations of flowing aa lavas, clearly demonstrate that the basal breccia is formed by spinose blocks tumbling down from the top in front of the slowly moving flow and being overridden by the flow itself.

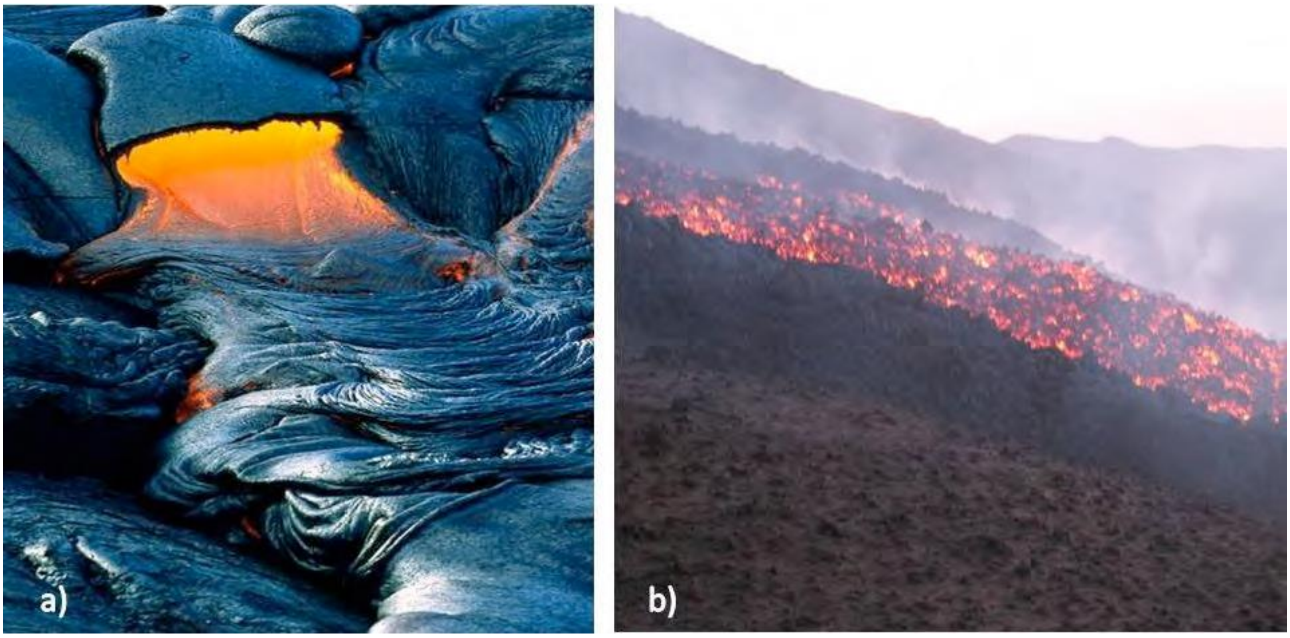

Figure 2.2. Basaltic lava flows. (a) Hawaiian pahoehoe flow characterised by low viscosity and plastically-deformed surface crust; typical “ropes” are visible. (b) Aa flow of Mount Etna: the higher amount of volatiles causes degassing during the flow leaking, favouring an early crystallization of the crust and a consequential breakup (De Berardinis, 2013)

Chemical and mineralogical analyses have shown that pahoehoe and aa lavas can be absolutely identical, thus magma composition and compositionally-governed viscosity, cannot be the reason for the contrasting flow behaviour. Fluid pahoehoe can change into aa when the viscosity and shear stress increase during flow but never the other way around. The shear stress, causing lava deformation, plays an important role on this change of behaviour, in fact at high shear stress when lava flows down a steep slope, aa can form much more easily out of pahoehoe (at constant temperature and therefore viscosity) than at low strain rate.

Another major factor in changing pahoehoe into aa lava, is that aa lava flows consist of moving lava clumps with the consequential growth of microlites during flow.

Understanding what kind of basaltic flow is involved on the formation of a lava tube is an important step, because these two types of lava flows give rise to a pyroduct through different mechanism of formation.

There are two different mechanisms of formation for lava tubes: **inflation** (Hon at al. 1994) and **crusting over** of channels, that occur through closure by slab jam and closure by lateral shelf growth (Kempe, 2010).

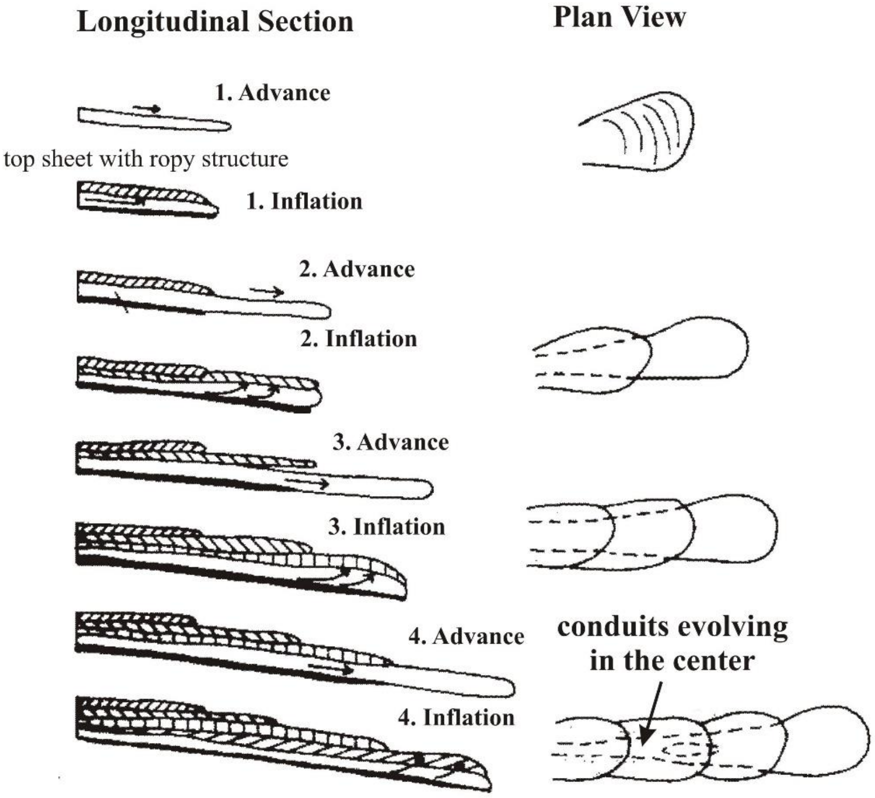

Figure 2.3. Sketch illustrating pyroduct (lava tunnel) formation. At the tip of a pahoehoe flow, lava advances quickly in form of a delta of thin, ropy lava. The next pulse of lava lifts the first sheet up (inflation). This process is repeated until a stack of lava sheets (the primary roof) is formed below which the hottest flow thread becomes the later main conduit (Kempe, 2012).

The **inflation** process (fig. 2.3) is typical of pahoehoe flows but can also occur in aa-type lava flows. During this process, pahoehoe lavas grow at their distal tips where hot lava quickly covers the ground in thin sheets that cool quickly causing the dissolved gases to form vesicles that diminish the overall density of the lava. The next advance will lift these sheets up (“inflation”) before forming the next distal surface sheet and in this way the precedent sheet will float on top of the next pulse because of buoyancy. The process can be repeated many times, forming a primary roof with several sheets with the oldest one at the top of the sequence which is the only one to display the typical ropy structure (fig. 2.4).

It is a misconception that the roof is upheld by the lava flowing below by buoyancy. Inflationary lava cave roofs hold up because they form low natural vaults with their weight resting on the walls (Kempe, 2010).

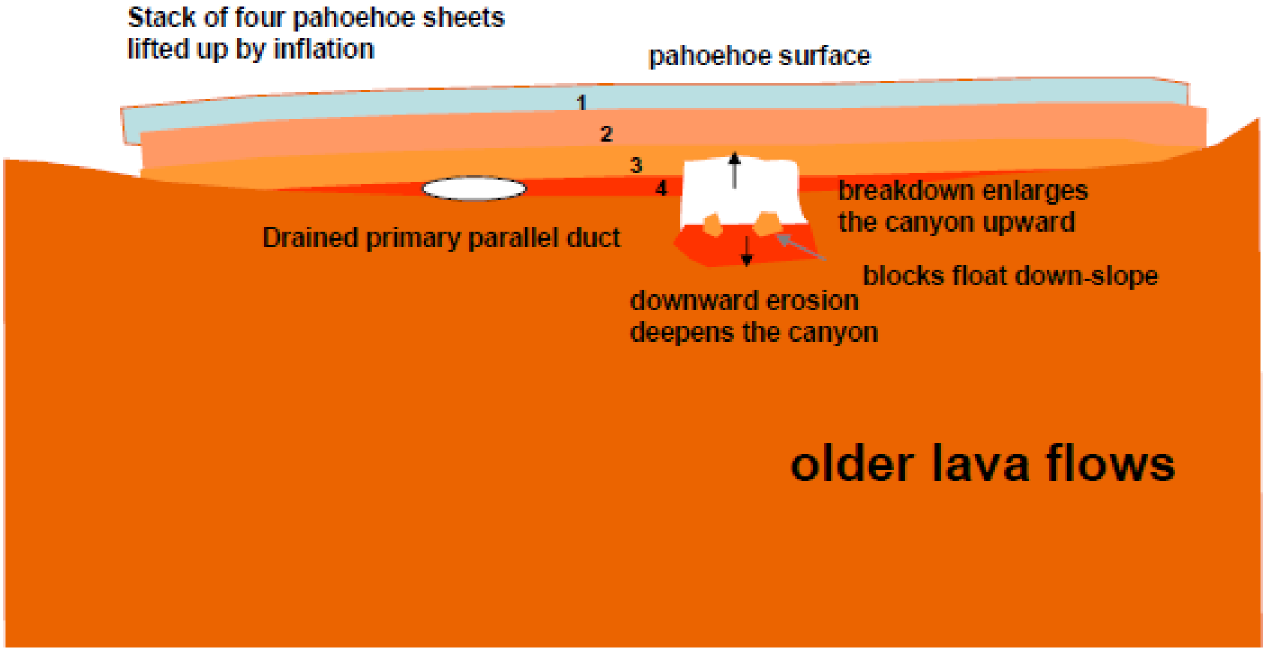

Figure 2.4. Sketch of the structure of a primary roof formed by “inflation” (Kempe, 2010).

Inflation in aa flows although rarely, occurs in a similar way to what is stated for pahoehoe flows. This is not a continuous long-lasting process but happens for short periods of time, generally from hours to a few days and is typical of the distal portions of a lava flow field. In this part, the rapid advance of the flow front expands over a slightly sloping substrate until its continued advance is prevented by topography and eventually by cooling of the flow front. The gradual reduction in advance rate of flow front causes widening and thickening of the flow. The flow front stops advancing and the flow inflates from the front region backwards and when the pressure of the lava that is accumulating inside exceeds the resistance of the crust, the opening of an ephemeral vent occurs a few tens of meters behind the flow front, where the crust is thinner than at the tips of the flow. This vent leads the drainage with the formation of a new flow. If this process takes place slowly enough to allow the cooling and hardening of the surface crust of the first flow, a new sector of a lava tube will form in this distal zone of the flow (fig 2.5).

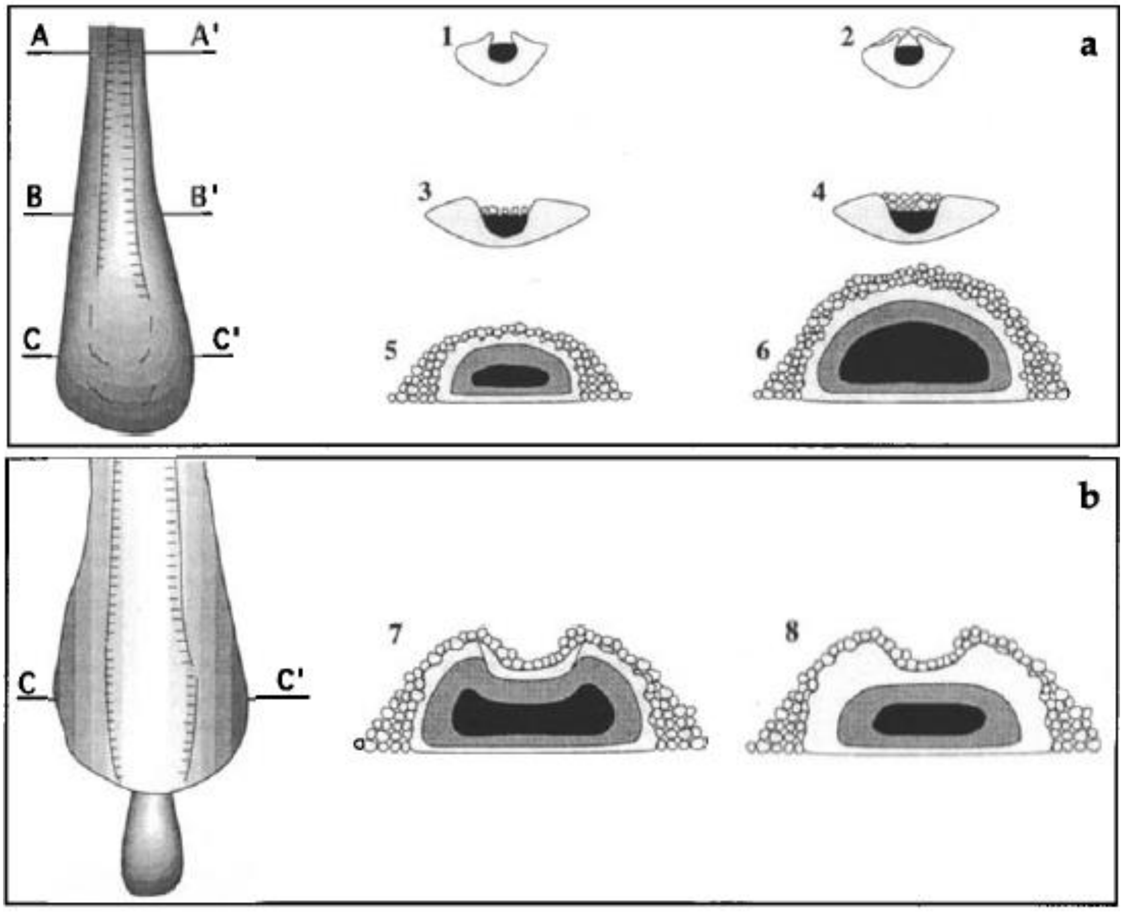

Figure 2.5. (a) Plan view of an arterial aa lava flow (left) and of six idealized sections along its proximal (AA', sections 1 and 2), medial (B-B', sections 3 and 4), and distal (C-C', sections 5 and 6) portions. In all sections, the isothermal interior of the flow is black, the viscoplastic layer is dark grey, and the brittle crust is light grey. Sections to the right (sections 2, 4, and 6) show a more evolved situation compared to sections to the left (sections 1, 3, and 5). (b) Plan view of a lava flow showing the opening of a first-order ephemeral vent at flow front (left), and cross sections (7 and 8) along its frontal region (C-C') showing the evolution (from 7 to 8) of the inflated portion of the lava flow when a new vent opens at its base (Calvari and Pinkerton, 1998).

Another mode is the **crusting over** of channels that appears to have two cases: **closure by slab jam** and **closure by lateral shelf growth**.

In the first case, shoals, blocks, lava balls and secondary clasts of already solidified lava form a “log jam” on the surface of a channelized pahoehoe lava flow. This jam is highly porous and not very stable but since it floats on the channel, it is injected by molten lava from below that, once solidified, welds together the blocks (fig. 2.6). In this way the roof is gaining mass and stability. The high porosity allows air to circulate through the forming roof, not only oxidizing the lava slabs turning them reddish, but also freezing-out layers of lining originating from the top of the hot lava in the channel (Kempe, 2010). Once roof is established, it can also be reinforced by later overbank events depositing layers of lava on top of the roof. This forming process can occur also in the medial portions of aa flow fields (fig. 2.5a).

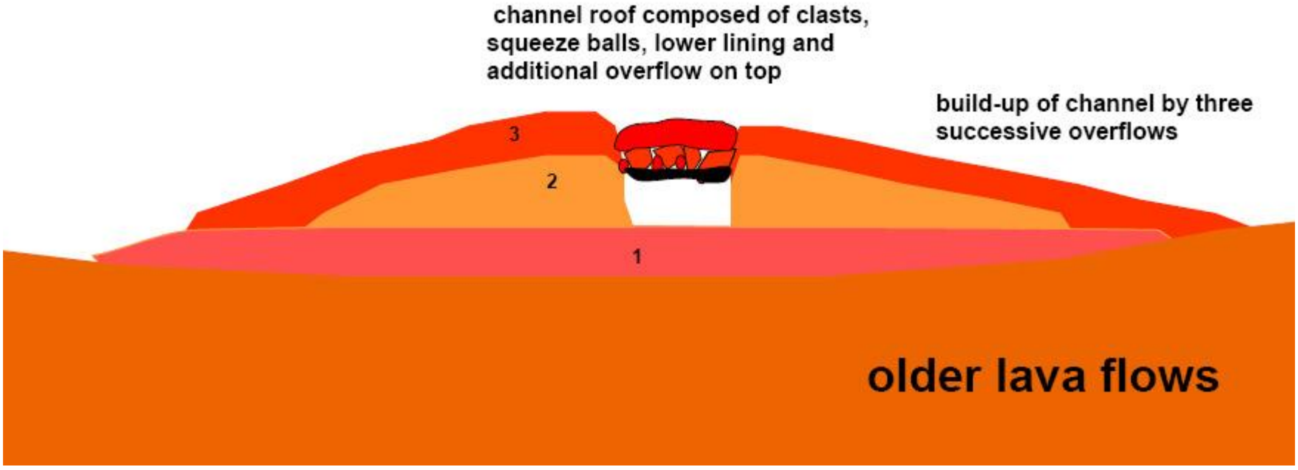

Figure 2.6. Scheme of a cross-section through a roof, formed by the crusting-over of a channel by the agglomeration of floating clasts (Kempe, 2010).

Closure by lateral shelf accretion is common in channelized aa lava flows, mainly in the proximal portions of the flow field (fig. 2.5a): the flow cools rapidly at the margins concentrating their movement in the central part of the path. As indicated by Kempe (2012), the formation of the roof occurs by accretion of vertical to sub-vertical thin lava layers through overbank events or stranded lava floats, that grow from the sides inward having a central vertical parting where the growing lateral shelves meet (fig. 2.7). Sometimes there may be the concurring effect of lateral shelf growth and closure by slab jam.

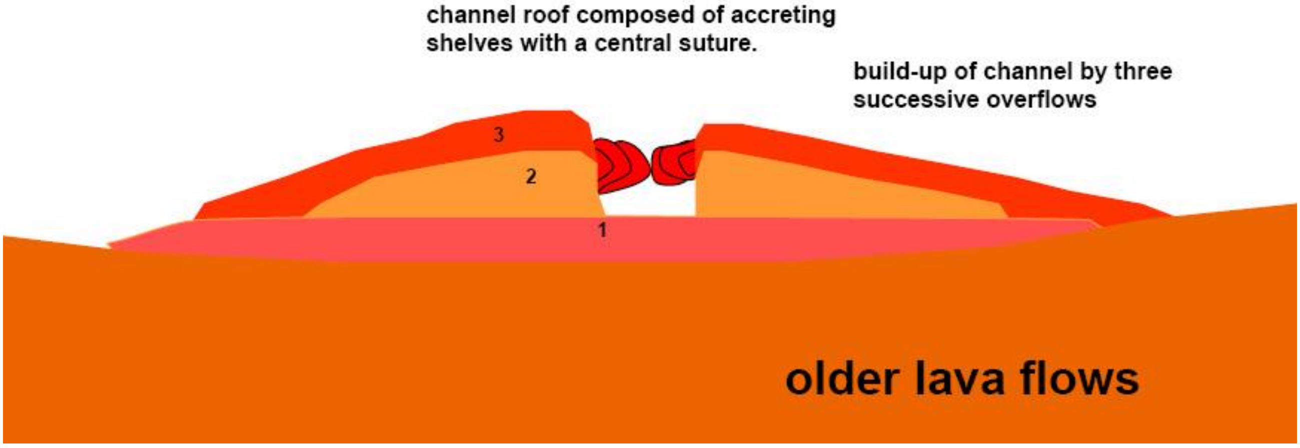

Figure 2.7. Scheme of a cross-section through a roof, formed by the crusting-over of a channel by accretion of levees (Kempe, 2010).

It has not yet been cleared what factors control the occurrence of a cave-forming process rather than another. Kempe (2010) suggests that differences in slope cannot be the governing factor, but rather the flow rate is important on the differentiating between the two mechanisms of formation.

Another important point is the occurrence of a relation between the size of lava tubes and their forming processes. It seems that no connection exists among these two aspects but rather the size of the section of a lava tube is due to the downcutting erosion (both mechanical and thermal) at the floor of the tube, the partial or total drainage, the breakdown phenomena and the coalescence of flanked or overlapping tubes (De Berardinis, 2013).

Anyway, in general, the overcrusted lava tubes are smaller than inflationary ones because are single or double-trunked and not of superimposed-trunked type.

Also the flow rate of lava through a tube is an important aspect that may define the size of the tube system: wider and longer tubes forming at higher discharge rates (Calvari and Pinkerton, 1998).

2.2 MORPHOLOGIES

There are a huge number of structures and morphologies related to lava tubes, some of these external, such as skylights, tumuli, ephemeral vent and hornitos, that help on the individuation of the tube’s path, and others internal, left by the passage of lava flows through the tunnel when the cave was active or during the early cooling stage.

Most of these internal morphologies are similar to those in limestone caves, such as stalactites and stalagmites, helictites, and a sort of flowstone. Also the formation of secondary minerals are typical inner features but tend to be on a much smaller scale than in limestone caves. They may be sulfate minerals such as gypsum and thenardite (sodium sulfate), but also calcite is common as well.

In some parts of the world, where the temperatures are low enough, ice can form spectacular features inside a cave.

In this work, I deal with only the morphologies that have been recognized inside and outside the lava tube of the volcano La Corona.

2.2.1 OUTER FEAUTURES

SKYLIGHTS

Among the external features of a lava tube there are, undoubtedly, the skylights (fig. 2.8).

A skylight is an opening to the surface formed where a portion of a lava tube's ceiling has either collapsed or, less commonly, been blown out from within and is relatively small in relation to the cave, reflecting more or less the diameter of the underlying passage. If a collapse occurs after the tube has drained, a breakdown pile will be evident beneath the skylight, but if the tube is still active or becomes active again later, the breakdown might become coated with lava forming a welded breakdown or carried away by the flow.

The skylights constitute the main accesses to lava tubes.

Figure 2.8. This view shows a typical collapse along a large passage segment of La Corona lava tube. Note the large breakdown pile from the ceiling collapse, indicating it occurred after the tube had active flow. Most of the time, the large passage both upflow and downflow are visible (in this case, upflow passage is shown).

2.2.2 INNER FEATURES

While lava tubes tend to be sinuous in plan view, the cross-sections vary from tall and narrow, to classic elliptical tubes or keyhole-shaped as a result either of erosion or coating events caused by the movement of lava flows inside the conduct. Lava caves start out as more elliptical, wider relative to height and over time become taller as flowing lava melts and erodes down into the floor of the tunnel. In general, the taller a passage the longer it was an active conduit. Passages can also be stacked, with new passages forming over older ones.

Another important inner feature of a lava tube, is the colour that assumes lava on the walls of the tunnel. The colour lava takes, depends on both its chemical composition and oxidation state because iron, in the lava, may oxidize to red hematite on exposure to air and in fact red lavas are often found around skylights that bring fresh air into the tube.

BREAKDOWNS

Pieces of lava tube’s ceiling or wall that have broken off and fallen to the floor are called breakdowns or rockfalls. Much of these collapses occur during the cooling phase, during shrinkage and contraction of the tube’s lining, causing some pieces to break off. Many other rockfalls occur during the reduced flow that precedes the deposition of linings (early rockfall).

As mentioned before, breakdown of the ceiling may also make an opening to the surface called skylight (fig. 2.8).

WINDOWS

A window is a collapsed opening between levels of a lava tube with several levels, one stacked above another.

Lower levels, usually the last part of the tube to be active, may overflow into upper levels through windows, leaving a thin deposit along the edges or sealing them completely.

LAVA SEALS

Seals of the conduit (fig. 2.9) may form in the downflow direction when breakdown blocks a passage and the flow is insufficient to overflow or carry off the breakdown, where the passage becomes smaller or because of the lowering of the ceiling. Alternatively, later flows may invade an existing tube and seal off passages.

Figure 2.9. Lava seal from Bunnell (2008).

CUPOLAS

A cupola is a dome-like heightening in the ceiling and is sometimes found in lower-level passages beneath windows that have become plugged or can also occur where lava under pressure caused melting upwards into a hardened ceiling (fig. 2.10).

Figure 2.10. Cupola (Bunnell, 2008).

CUTBANKS

Concave sections of a tube wall formed by lava flows on the outside edge of a meandering passage, where the erosive force is greatest because velocity and turbulence are higher here.

Erosion occurs via melting and not simply by mechanical erosion because the higher velocity and turbulence serve to more efficiently convey heat to the outside portion of the wall causing greater melting. Cutbanks often form above aprons.

APRONS (SLIPBANKS)

A surface that slopes down from a lava tube’s wall is an apron and it tends to be more pronounced on the inside edge of a meandering lava tube passage, where the flow’s velocity is lowest allowing more lava to accumulate (fig. 2.11).

LEVEES

As a small stream of lava that does not fill the full width of the passages moves through an existing tube, the sides tend to cool first and create a vertical remnant along the edge. This process leads to the formation of a channel on the floor of the lava tube (fig. 2.11).

TUBE-IN-TUBE

Sometimes the levees tend to arch inward and if they join together, may form a shallow tube that does not continue very far and is generally no more than half a metre tall (fig. 2.11).

Figure 2.11. Apron and a small overcrusted lava tube inside the lava tube of La Corona. Credits: Robbie Shone.

SIPHONS

An earlier rockfall is likely to dam the lava streams and the dam may produce an inverted siphon as shown on fig. 2.12 (Harter, 1972).

LININGS

Any lava deposits within a lava tube is a lining. When lava flows pass through an established tube, they may accrete material on the walls in thin layers called linings and where a large portion of wall has fallen, a number of distinct layers can be visible (up to a dozen).

There are several types of lining on the basis of their position inside the tube. (fig 2.12).

Floor lining. It may be constituted by a lava stream, or a remnant of it, that stops its run within the lava tube and sometimes it can contain an unroofed channel (see levee definition). The formation of the floor lining begins with a reduced stream flow filling only the bottom tenth of the lava tube: such a shallow stream is unable to maintain heat so it cools by several hundred degrees becoming highly viscous and slow (Harter, 1972).

Wall lining. It consists of three parts: the body, extending for most of the height, the base, tapering in a compound curve that terminates above floor level and the top, that forms a frame whose bottom surface is another compound curve. When a wall lining is very thin, it only consists of body that continue downward to the floor and terminating with a ragged upper edge.

Since the bottom edge of the wall lining coincides with the stream surface, a lining that continues to the floor represents a complete cessation of flow in the lava tube.

Ceiling lining. It is wall lining in which the stream crest completely filled the conduct. The formation of ceiling lining occurs when gas bubbles in the flowing lava rise until they reach the underside of the lining, where they collect; when a frothy layer has formed, it suddenly collapses into a layer of gas that is a good insulator and mechanically strong enough to support the lining (Harter, 1972). Once the froth collapses, it leaves a ceiling with a coating of molten lava. Here is common the formation of lava stalactites (see lava stalactites section).

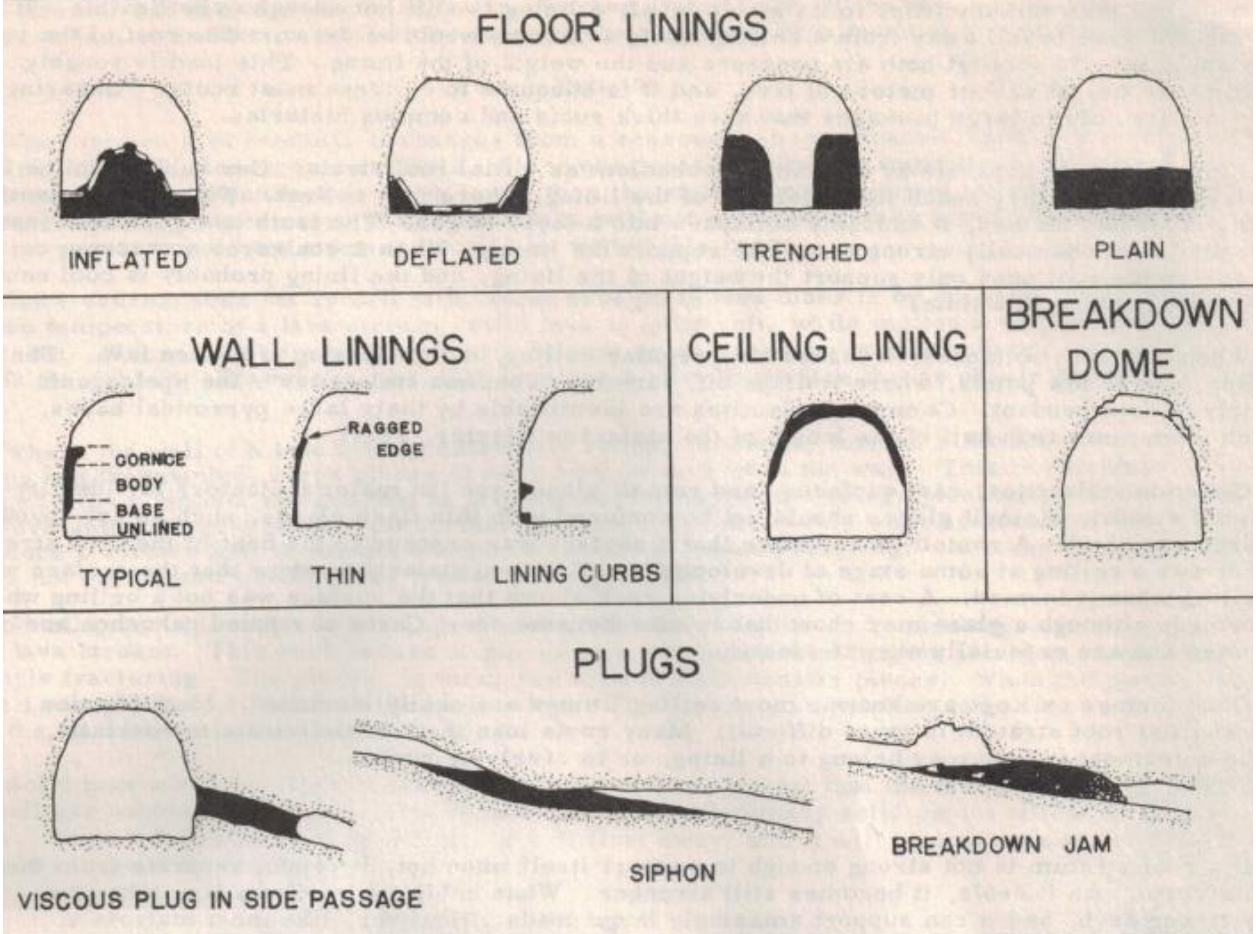

Figure 2.12. Forms of passage modifications in lava tubes (Harter, 1972).

LAVA STALACTITES

Lava stalactites are a type of ceiling lining and come in three main varieties, shark-tooth, splash and tubular but the shark-tooth stalactites are the most common. As the level of flowing lava inside an active tube fluctuates, it may coat protrusions on the ceiling with a thin film of lava. Otherwise, small drops of lava can form as a molten ceiling is cooling, either during the initial flow or when a later flow through an existing tube causes remelting.

These stalactites tend to occur in dense clusters rather than solitary individuals and can vary from one centimetre to metre in length (fig. 2.13).

Figure 2.13. Lava drops from the lava tube of La Corona.

CONTRACTION CRACKS

As the interior of a drained tube cools, shrinkage occurs and cracks form in the walls and floors (fig. 2.14).

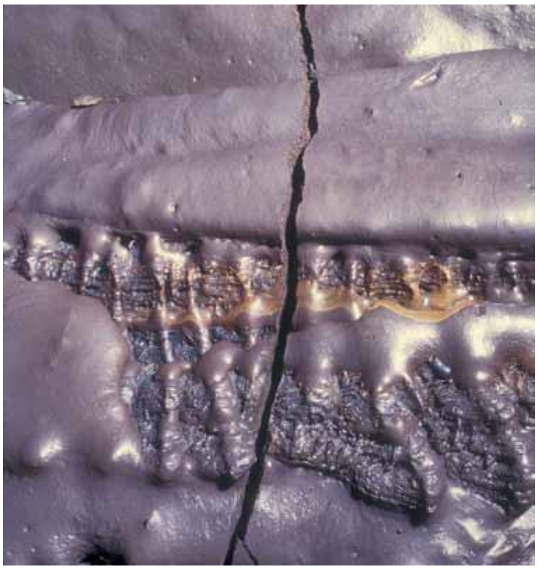

Figure 2.14. Contraction cracks from Bunnell (2008).

FLOW LINES

Flowing lava leaves its mark in many ways but the simplest of these are flow lines, etched into the walls of the cave. They may be thick or thin as well.

MINERAL DEPOSITS

As previously said, it is frequent to find several mineral deposits along the walls and the roofs of lava tubes whose formation occurs during or after caves' cooling phase (fig. 2.15, 2.16).

Deposits in form of crusts, crystals, stalactites and stalagmites, can occur in two major ways. As the cave initially cools, minerals can condense from gaseous vapours, typically forming crusts or small crystals. Alternatively, after the cave has formed, water from rainfall begins to seep in through the fractures of the roof and may slowly leach out minerals that can be re-deposited inside the cave.

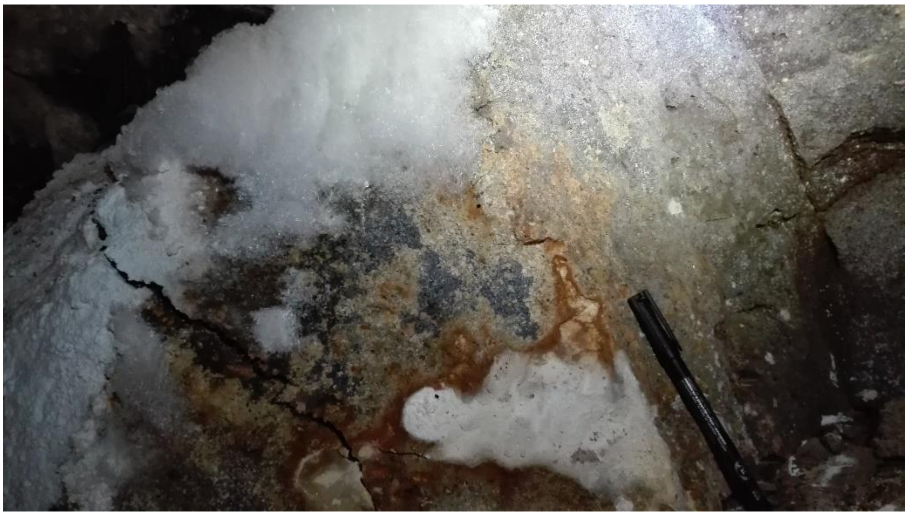

Figure 2.15. Mineral deposits in form of acicular clouds and white crusts from the lava tube of La Corona.

Figure 2.16. Mineral deposits in form of acicular clouds inside the lava tube of La Corona. Credits: Robbie Shone.

CHAPTER 3: METHODS

To create a detailed geological map, it is customary to integrate data collected from walk-over survey with data coming from remote sensing survey, not only to get an overall view of the investigated area from different point of view and different scales of observation, but to better investigate the parts of an outcrop that are not normally accessible, such as areas of outcrop that cannot be reached or examined from afar or cliff sections flanked by water. It turns out to be evident that also for the survey of caves, such as lava tubes, the employment of remote sensing becomes a very powerful mean.

In order to realize a good and detailed geological survey activity, it is good practice to start with remote sensing, mostly analysing and elaborating the satellite-based data of the area of interest through the use of apposite software such as ENVI or ArcGis. During the following fieldwork phase, it is possible, and most of the times necessary, to check and/or modify the previous interpretations with new data collected in the field and eventually other remote sensing techniques may be applicated.

First of all, with ArcGis, we started from the basemap and LIDAR-derived DTM of the northernmost part of Lanzarote to perform the first elaborations and afterwards during our fieldtrip on the island, we carried out a drone-based photogrammetric survey of some points of the Famara cliff and the scan of the most of the lava tube of La Corona from the inside with laser scanning technique.

Even though it is far from being a replacement for traditional fieldwork, LIDAR and photogrammetry and in general remote sensing, have been becoming more and more essential tools for the geologists.

3.1 SATELLITE-BASED REMOTE SENSING

Satellite-based remote sensing, include the acquisition, elaboration and interpretation of satellite data, both optic and radar.

First of all, in the ArcGis environment we have used the basemap provided from different satellites (Esri, DigitalGlobe, GeoEye).

The first step has been the recognizing and highlighting of lava flows’ fronts of La Corona, Los Helechos and La Quemada volcanoes. In this way it has been possible to get a whole view of the lava fields of this volcanic system, mainly observing the intersections among lava flows and speculating on spatial and temporal relations.

In order to do this, **hillshade** and **slope** raster have been created with ArcGis through the respective tools. The creation of these two raster requires the acquisition of DTM data, in this case provided by LIDAR.

The hillshade tool creates a shaded relief from a surface raster by considering the illumination source angle and shadows and, for each cell, it has an integer value ranging from 0 to 255 according to the illumination: cells in shadow have a value of 0 (desktop.arcgis.com).

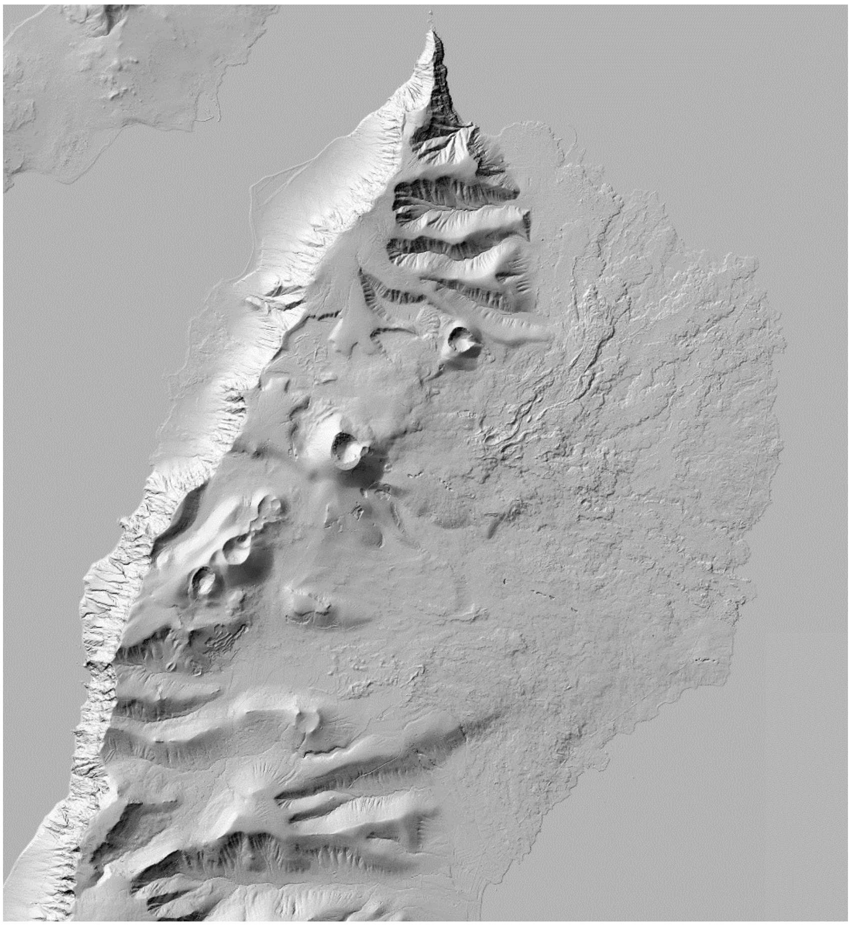

Figure 3.1. Hillshade raster of the area surveyed during our fieldwork obtained by ArcGis.

The slope tool identifies the slope as gradient or rate of maximum change in z-value (where z is the height) from each cell. The range of values in the output depends on the type of measurement unit: for degrees, the range of slope values is from 0 to 90 and for percent rise, the range is 0 to essentially infinity (desktop.arcgis.com). A flat surface is 0 percent, a 45 degrees surface is 100 percent, and as the surface becomes more vertical, the percent rise becomes increasingly higher.

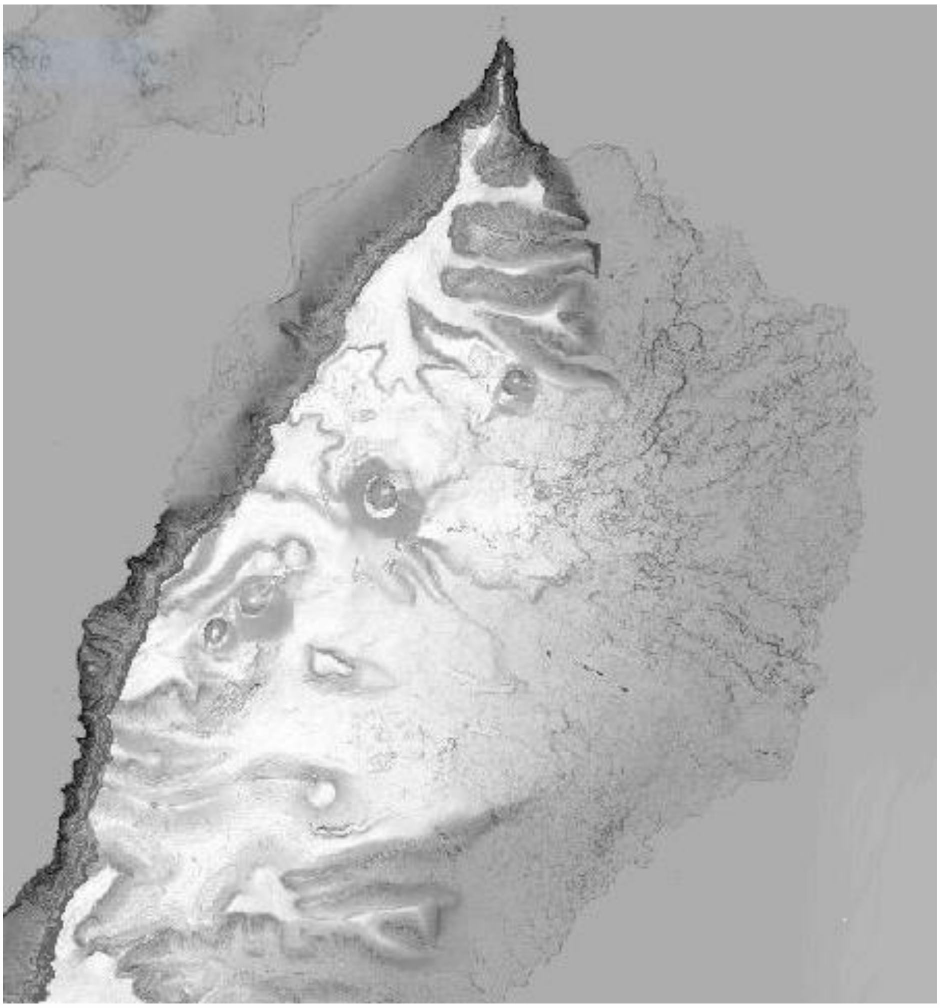

Figure 3.2. Slope raster of the area surveyed during our fieldwork obtained by ArcGis.

These rasters have helped on tracking of lava flows boundaries and on individuating stage and substage of the Famara shield volcano.

3.2 DRONE PHOTOGRAMMETRY

The photogrammetry is a technique that enables to metrically determine shape and position of an object, starting from a series of distinct photograms from which a software extract 3D data: hence, we can identify the spatial position of all the interesting points of the object in question.

This technique is used mostly for the topographic survey (mapping or thematic applications), especially in the form of aerial photogrammetry, for the building of DTMs, orthoimages, 2D and 3D reconstructions (Baltsavias, 1999).

For our photogrammetric surveys, we used the drone DJI Mavic Pro equipped with a very stable camera of 12 megapixel, a 78,8° field of view and a movement range (pitch) varying from -90° when pointed downward to +30° when tilted upward with respect to the drone position.

Figure 3.3. The drone DJI Mavic Pro used for photogrammetry.

During the photogrammetry phase, the drone took a number of photos of the area of interest from different points of view, from shifting up- and downward and laterally to the right and left and recording the GPS position of every photo. The amount of taken photos has been of 336. This process has been executed for three different areas of the Famara cliff: one on the western side of the massif, in proximity of the Camino de Los Gracioseros, and two on the eastern side, of which one near the village of Orzola and the other two/three hundreds of metres further north. Because of the closeness of the resulting models of the two sites near Orzola, they ended to intersect each other and for this reason we choose to join them in order two have one single model.

Figure 3.4. Satellite view of the three sites detected by drone for photogrammetry.

For the processing of the photos taken with the drone, we have used the software Agisoft Photoscan. In this way, we have obtained DEM and orthomosaic to be imported in ArcGis for the improvement of the geological map of the Famara cliff zone, in particular for the determination of the soils and sedimentary formations that evidence gaps in volcanic activity of the shield volcano.

A orthomosaic is a cluster of orthophotos that are orthorectified and georeferenced so that they result perfectly justified to a global reference system.

The procedure to be followed during the photogrammetric elaboration is usually constituted by the same passages for every software: the most used procedure is the so-called “structure from motion” (www.microgeo.it). This calculation technique allows building of the objects’ shape through the automatic collimation of several points from a cluster of images.

The first step is the **Image Alignment**, during which the structure from motion extracts the significant points from each photo, derives the photographic parameters and meets the recognisable points of several photos finding the spatial coordinates of these points. In this phase the automatic orientation of the pictures in a 3D space occurs. The extraction of the key points is important for the creation of a **sparse points cloud** that is the result of this first phase of elaboration.

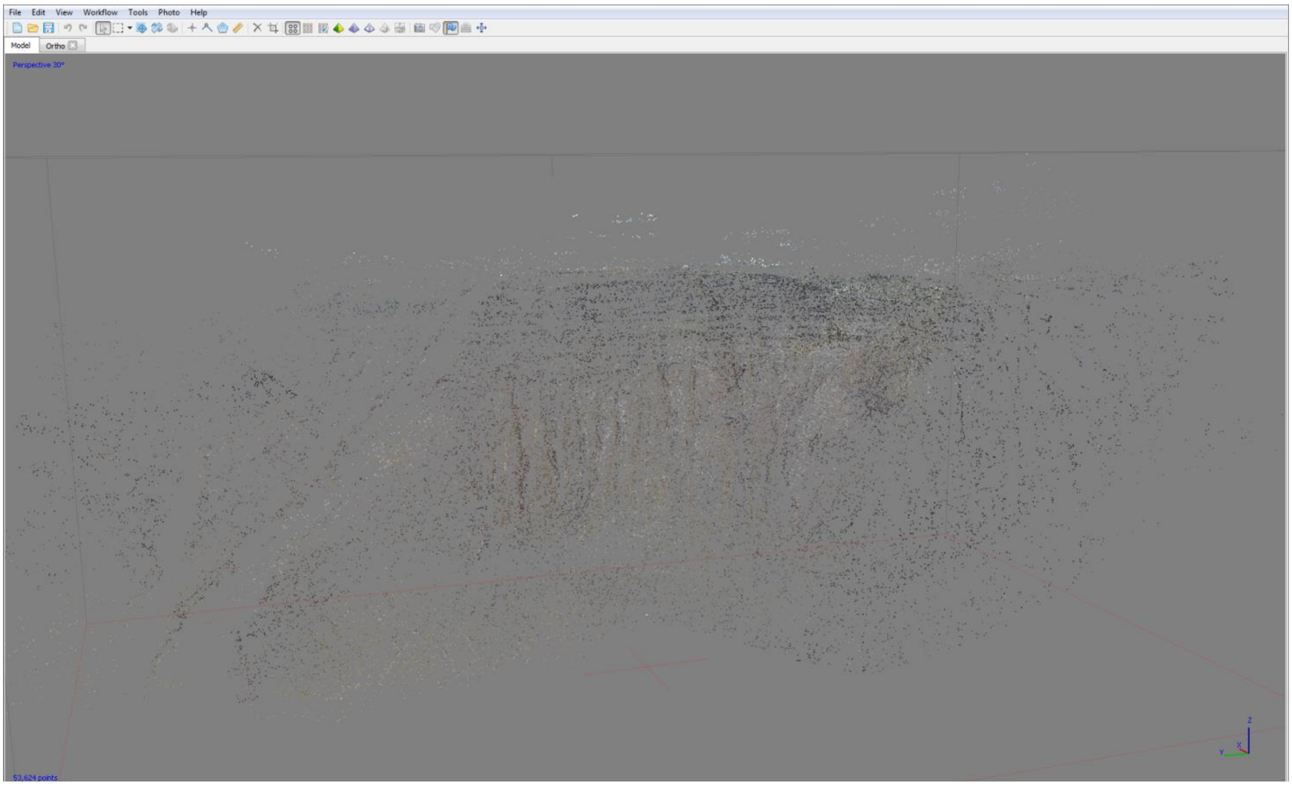

Figure 3.5. Snapshot of Photoscan showing the sparse points cloud of the area next to the Camino de Los Gracioseros.

We continued with the following stage that is the construction of the **dense points cloud**: once the program constrained the points of the sparse cloud, the densification of the previous points cloud occurs through the increasing.

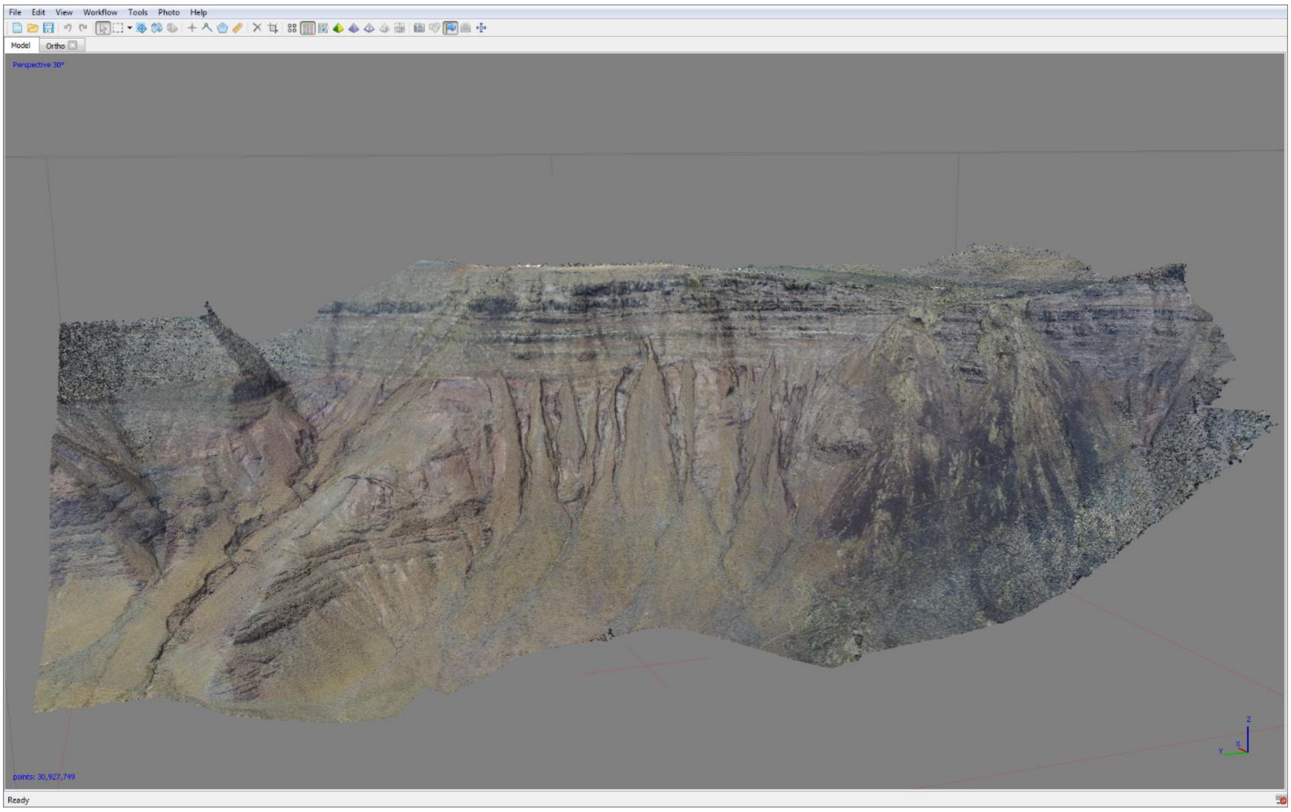

Figure 3.6. Snapshot of Photoscan showing the dense points cloud of the area next to the Camino de Los Gracioseros.

The dense cloud is the crude data useful for the following passages, such as the building of the mesh and the DTM.

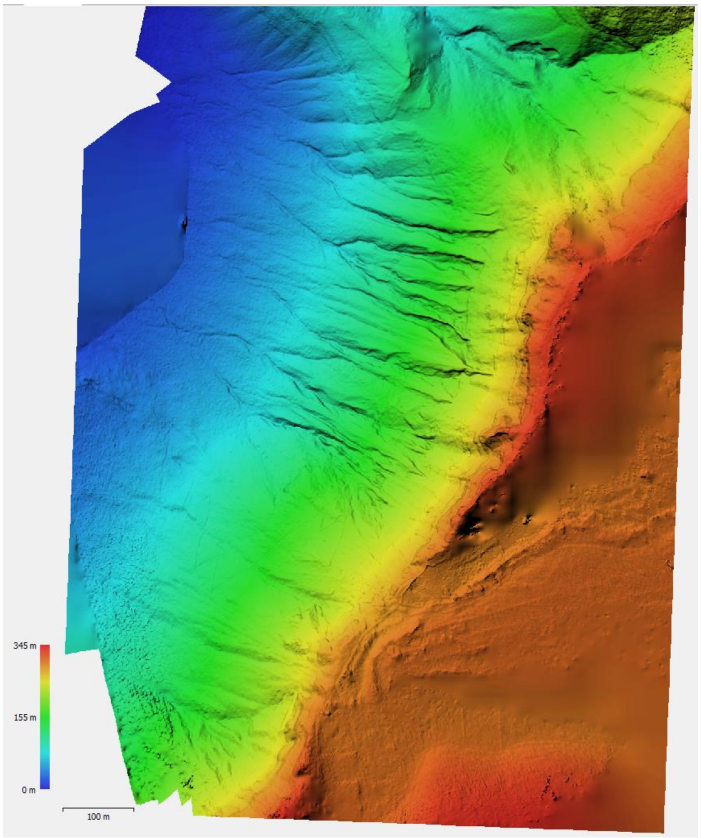

Figure 3.7. DTM obtained with Photoscan of the area next to the Camino de Los Gracioseros with a resolution of 0,20 m.

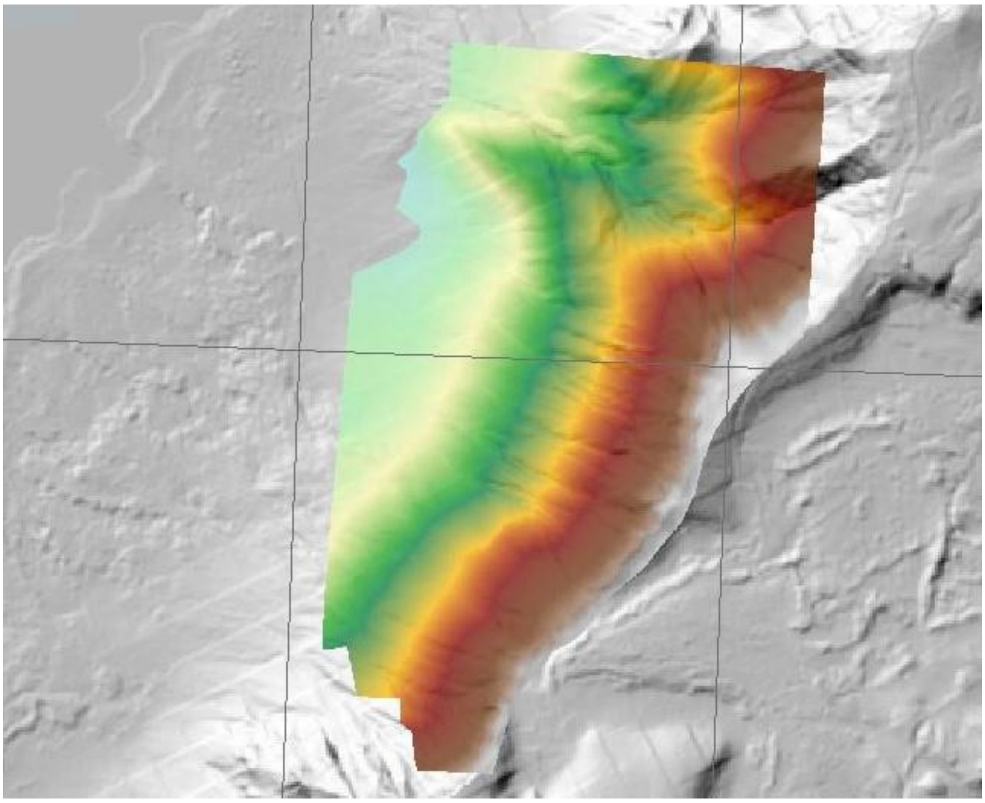

Figure 3.8. Snapshot of ArcGis showing the imported DTM and the hillshade raster of the area next to the Camino de Los Gracioseros.

The last phase of the photogrammetric elaboration is the realisation of the **mesh**, starting from the dense points cloud. It is a continuous surface made of triangular polygons whose vertexes correspond to the points of the cloud that are described by three-dimensional coordinates x,y,z. On this triangle-made surface, the structure from motion overlaps a texture map extracted from the original photos creating a photorealistic three-dimensional model.

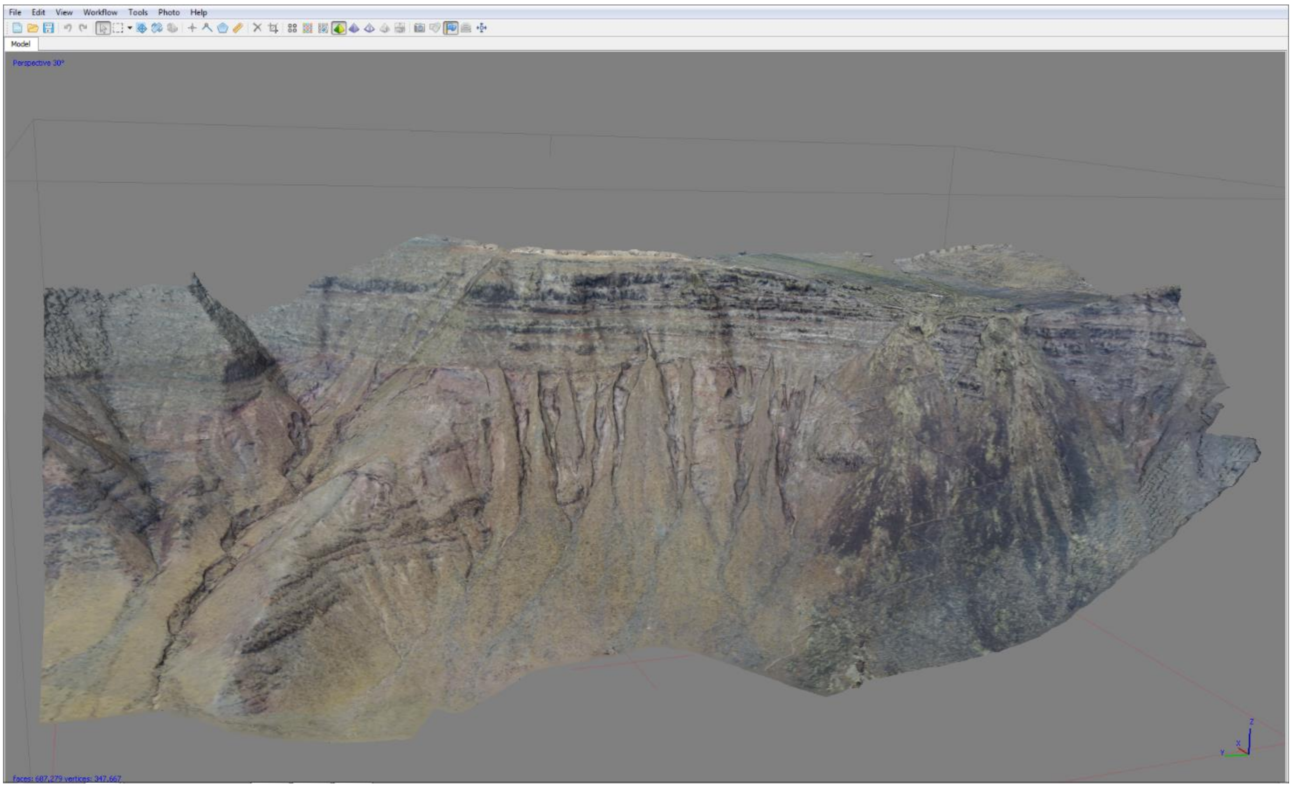

Figure 3.9. Snapshot of Photoscan showing the mesh of the area next to the Camino de Los Gracioseros.

Finally, always through Photoscan, we obtain the orthomosaic from the DEM that has been imported into the ArcGis environment since it is a useful mean for completing the geological map.

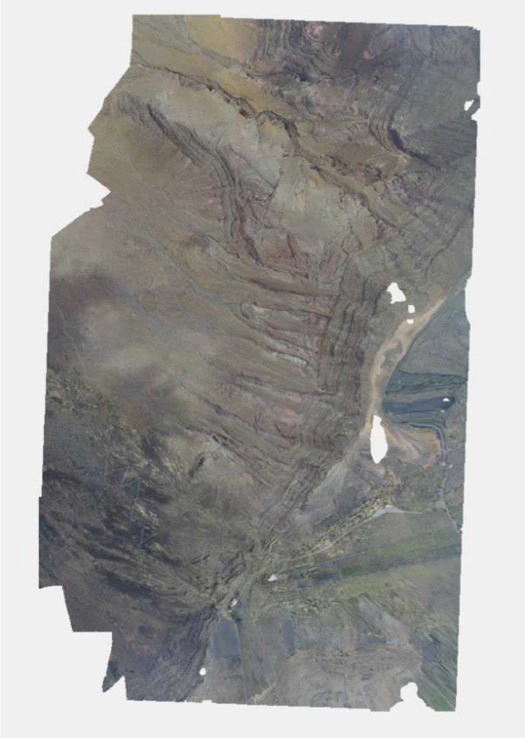

Figure 3.10. Orthomosaic obtained with Photoscan of the area next to the Camino de Los Gracioseros with the resolution of 0,90 m.

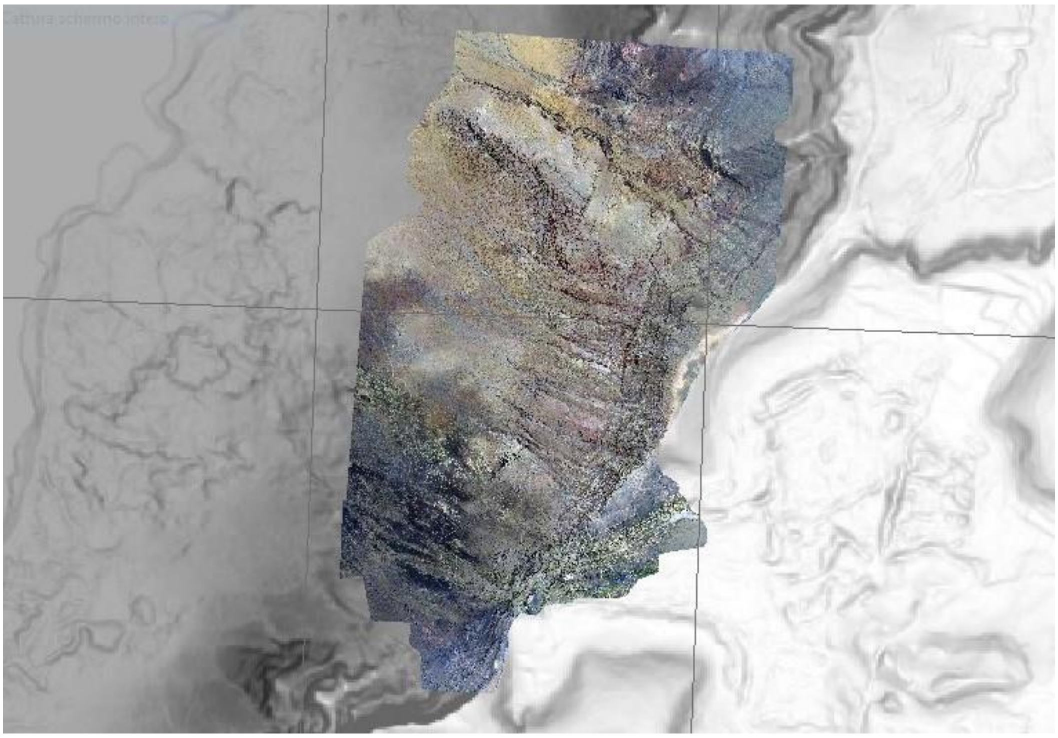

Figure 3.11. Snapshot of ArcGis showing the imported orthomosaic of the area next to the Camino de Los Gracioseros.

3.3 LASER SCANNING

The laser scanner is an instrument that enables the building of 3D models of objects, both artificial such as edifices and monuments and natural such as rocky outcrops, through the use of LIDAR technology.

The use of LIDAR technology, has brought, in the geological sphere, to the realisation of digital terrain models (DTMs) and virtual outcrop models for the monitoring of slope stability and open pit mine sites, for morphological reconstructions of geological settings, for detailed mapping of volcanoes, lava flow, dikes, fissures, faults, folds, glaciers, drainage morphology and for numerical modelling of geological phenomena.

The high spatial and temporal resolution has allowed this technology to become one of the most effective tool available for the collection of detailed and accurate geological data that can be exported into various software platforms for different kinds of geological analyses.

The word “LIDAR” is an acronym for *Light Detection and Ranging*. It operates by emitting intense focused beams of light to a target, in order to measure the time that the reflected light spends to return to the instrument and be detected by the sensor: these informations enable the calculation of the distance between the device and the target and the building of 3D models, DTMs at detailed resolutions (Karamitros, 2016). Moreover, the fact that LIDAR is illuminating a target with a laser and analysing the reflected light, allows scan data to be collected during the night or inside a cave as in our case when the conditions are usually less favourable.

Nowadays, there are two major categories of LIDAR technology, the TLS (Terrestrial Laser Scanning) or T-LIDAR and the airborne LIDAR according to the data's purpose, the size of the area to be captured, the range of measurement desired, the cost of equipment and more.

In this work, for the scanning of the lava tube we used the laser scanner Leica HDS 7000. It is a T-LIDAR supplied by a mobile head spinning around of 360° during the acquisition phase: this instrument allows recording of more than one million points per second with a maximum range of 187 metres (hds.leica-geosystems.com). Even though a low scan speed enables to get high-quality data, in the case of Leica HDS 7000 the ultra-high scan speed does not compromise the accuracy.

Figure 3.12. The laser scanner Leica HDS 7000 used for the scanning of the lava tube of La Corona.

During the acquisition, the instrument stores, for each detected point, the distance and horizontal and vertical angles on the basis of its position.

The resulting product is once again a points cloud that may be visualised and analysed through a number of software: from the points clouds it is possible to get a 3D model, thanks to the building of the mesh, or a DTM (or DEM) in a similar way to the procedure of photogrammetry explained beforehand (www.microgeo.it).

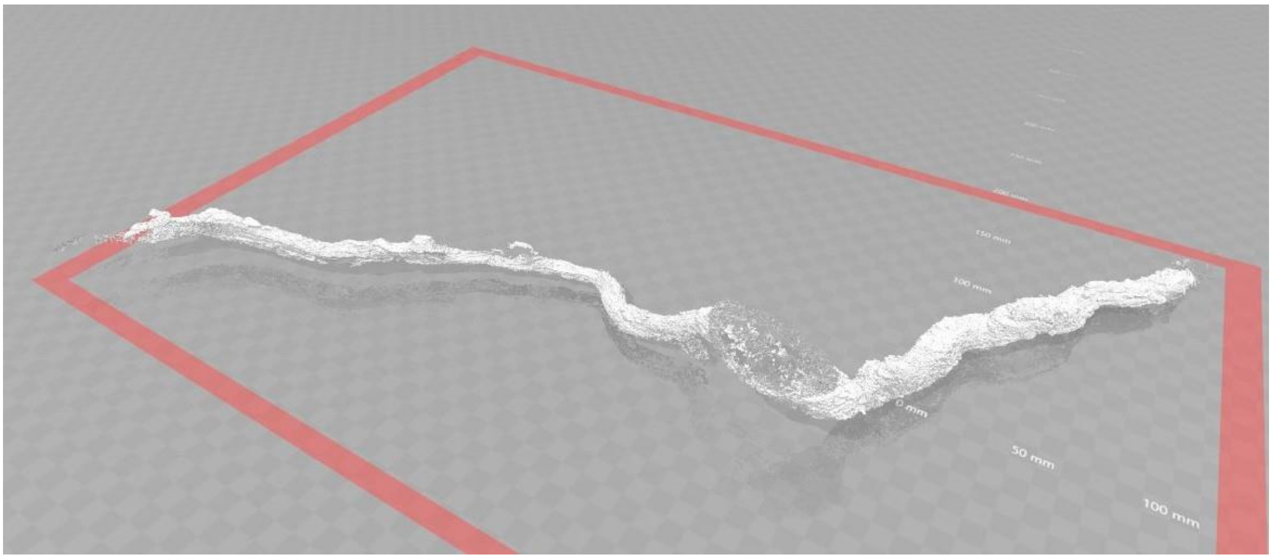

Figure 3.13. 3D model of the portion of lava tube down- and upstream of the Jameo de La Gente. The total length is about 1700 metres.

CHAPTER 4: FIELDWORK ACTIVITY

Our fieldwork has interested the northernmost part of the island of Lanzarote, more or less correspondent to the municipality of Haría. One part of our activity was a classical field-work, by checking geological limits already drawn through remote sensing interpretation and looking for stratigraphic markers while another part has been conducted inside a portion of the lava tube of La Corona to understand the processes ongoing during its origin and evolution.

4.1 OUTDOOR FIELDWORK

During this phase of our work we have been able to improve the description and the role of the main geological formations of the surveyed area and sometimes the photogrammetry has been a valuable help.

From the results of the outdoor activity, we suggest of dividing the area in three different complexes, from the lower to the upper: the Famara complex, the lapilli horizon and the Quaternary volcanic complex, composed by the Los Helechos – La Corona – La Quemada system.

4.1.1 THE FAMARA COMPLEX

The Famara massif is the lower complex of the investigated zone and we have checked out two distinct areas that correspond roughly to those surveyed by the drone-based photogrammetry.

On the eastern side of the Famara cliff, following a path starting from the beach of Orzóla, we have arrived to an inlet at the base of the cliff called in Spanish “Valle Chico”, characterised by a contact zone between basaltic lava flows and light pyroclastic deposits.

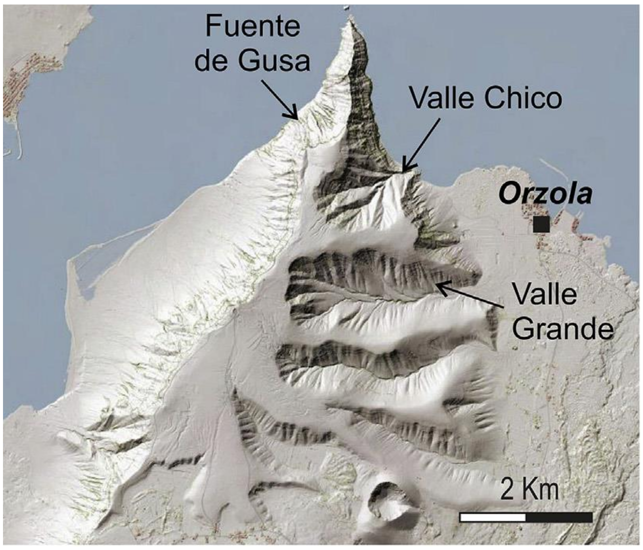

Fig. 4.1. Location of the sites of Valle Chico and Valle Grande on the Famara massif (Lomoschitz et al., 2016).

Interposed between the two lithologies there is a yellow to reddish sedimentary bed that clearly marks a gap period in the volcanic activity of the Famara complex.
The stratigraphic section of this cove (fig. 4.2) from the bottom to the top is made of light welded pyroclastic material, a 50 centimetres-thick bed of volcanic breccia with an intense carbonate veining, a bed of about 3 metres of bioclastic calcarenite with volcanic grains and some evaporitic levels, 2 metres-thick conglomerate/coarse sandstone with volcanic fragments and a 1.5 metres-thick bed of volcanic breccia with red fine matrix and some bioclasts (Lomoschitz et al., 2016) and basaltic lava flows that continue up to the top of the cliff.

Fig 4.2. The outcrop of Valle Chico showing the contact zone between the pyroclastic deposits and the basaltic lava flows. Credits: Robbie Shone.

By continuing along the path, we have been able to follow pretty well the sedimentary layer observing the thinning of the beds that reach the thickness of 2-3 metres after 250 metres (fig. 4.3). From here, we have observed that this sedimentary bed is continuous until the northern tip of the Famara massif and that probably keep going on the other side of the cliff (fig. 4.4).

Figure 4.3. Sandstones and conglomerates below the basaltic lava flows just north Valle Chico.

Figure 4.4. Sandstones and conglomerates below the basaltic lava flows just north Valle Chico. On the right it is possible to follow this bed along the cliff.

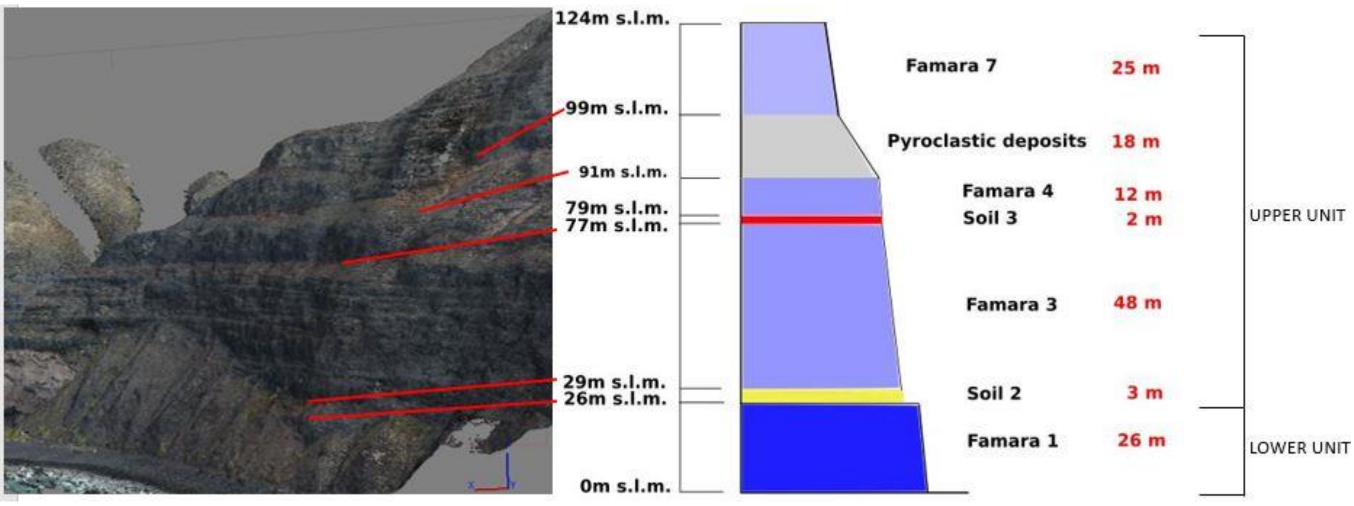

Figure 4.5. Stratigraphic section of the Famara cliff 250 metres north to Valle Chico correlated with the 3D model. The altitudes are based on the DTM derived by the photogrammetry.

The same contact zone between basalts and pyroclastic deposits, resurfaces just south Valle Chico, on the slope of the massif facing the village of Orzóla and follows a variable path, rising toward the centre of the outcrop and then down again (fig. 4.6). This boundary with the interposed described sedimentary bed, is continuous for at least five hundred metres until “Valle Grande” in a huge and spectacular outcrop: climbing the slope until the contact we have noticed a reddish sandstone and a conglomerate with a red matrix and an intense veining between the basalts and the pyroclastic materials (fig 4.7a).

The stratification of these welded ashes and lapilli is more or less plane parallel looking on the southern part of the outcrop but it becomes more inclined toward the north. We have measured the attitude of the pyroclastic layers in two points close together: in the first point, the compass has shown a value of 275°/7° (respectively dip direction and dip) and in the second one just north 290°/20°, according to the increasing of the dip northwards (fig. 4.7b).

The lava flows above this boundary are fractured and we have identified the occurrence of huge structures of onion skin weathering suggesting an enhanced water alteration (fig. 4.8).

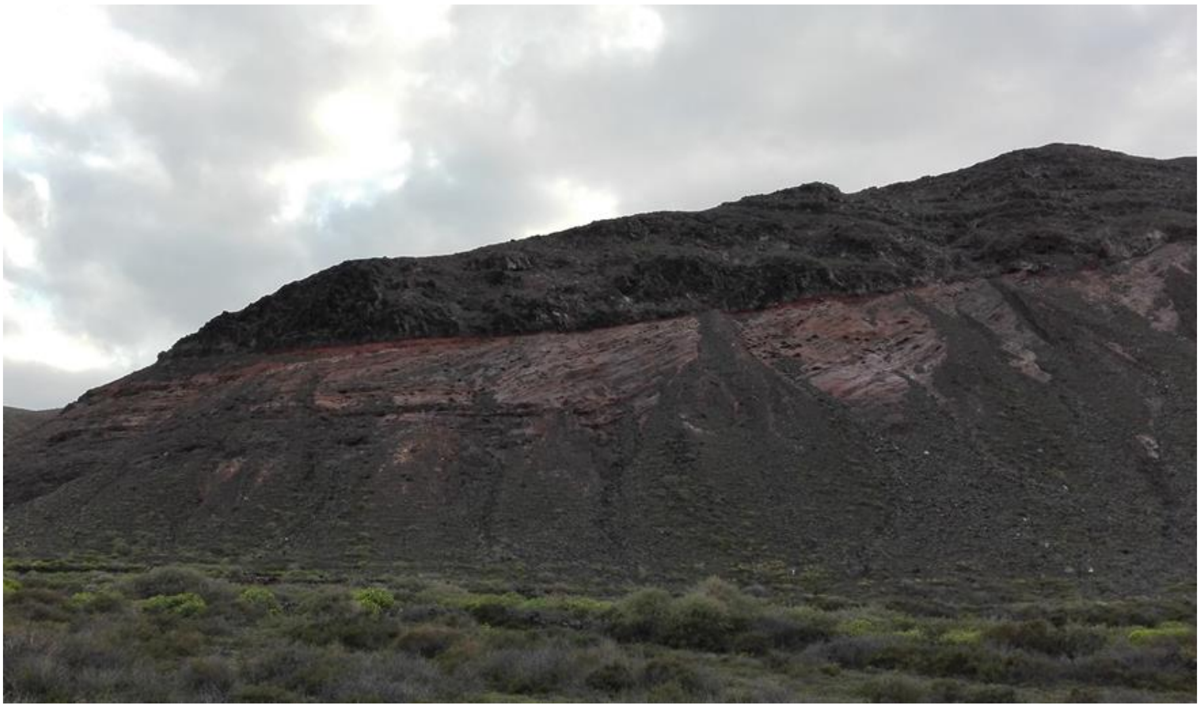

Figure 4.6. Outcrop showing the contact between the pyroclastic deposits and the basaltic lava flows in front of Orzóla.

Figure 4.7. a) Red soil underneath the basalts. b) Pyroclastic deposits just below the soil.

Figure 4.8. Onion skin weathering affecting the basalts just above the red soil.

On the western side of the Famara massif, it is possible to notice the reddish soils and lava flows that build up the cliff (fig. 4.9). From the base of the slope, we have had a beautiful panoramic view of most of the western side of Famara and from here we have been able to improve our geological map, by better tracking the lavafall, the soils and the boundary between the basaltic flows and the pinkish pyroclastic deposits that is most likely the same observed near Orzóla.

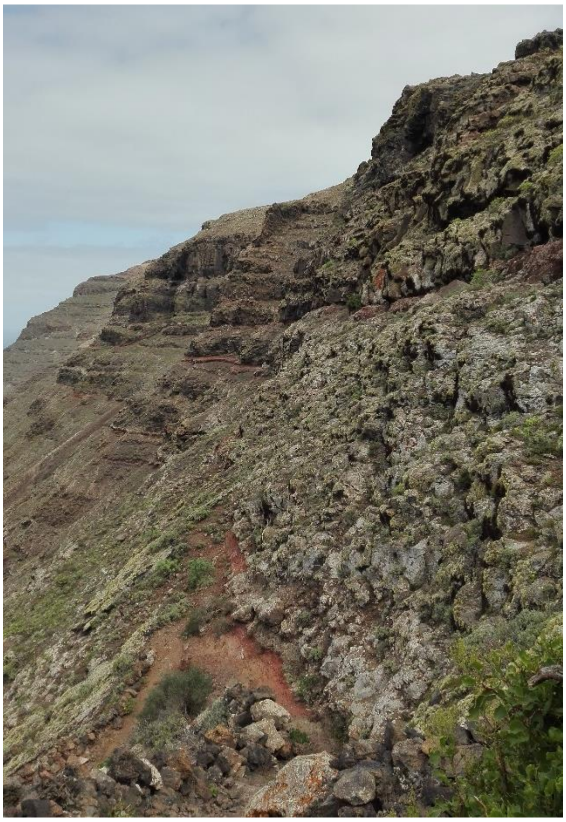

Figure 4.9. The western Famara cliff with basaltic lava flows and the interlayered soils.

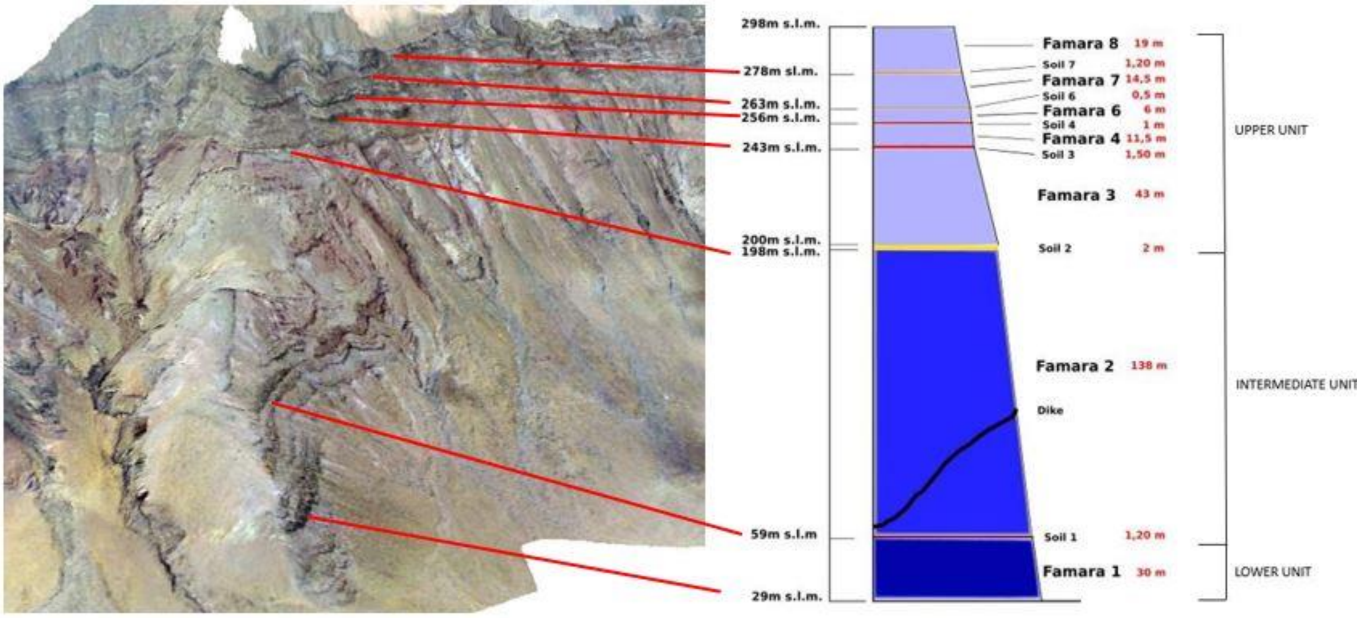

Figure 4.10. Stratigraphic section of the western Famara cliff correlated with the orthomosaic. The altitudes are based on the DTM derived by the photogrammetry.

On this side of Famara massif, intensively fractured and altered basalts outcrop at the bottom of the slope showing carbonate-filled fractures and some interlayered levels of caliche. The formation of caliche is a characteristic feature of Lanzarote and its arid climate: in fact, the intense evaporation of the water favours the deposition of carbonate (fig. 4.11). Hence these layers are hints for gaps in the volcanic activity between different volcanic flow successions.

Along this slope of the Famara massif we have seen some dykes crossing the pyroclastic deposits and some of them ending against the overlying basaltic lava flows, as highlighted by the photogrammetry (fig. 4.12).

Figure 4.11. Fractured basalts with interlayered carbonatic material (caliche).

Figure 4.12. Drone view of the cliff showing the dikes swarm.

The top surface of the northern Famara massif is relatively flat with a progressive downgrading toward its extreme tip at the north and, where not covered by the Quaternary volcanic complexes, it is made of a yellow-brownish soil that is often permeated of several levels and lenses of caliche (fig. 4.13).

Figure 4.13. Picture showing the soil that covers the top of the massif.

4.1.2 LAPILLI LAYER

This complex is made of unwelded dark lapilli and ashes with a frequent superficial alteration that in the upper part imparts them a yellowish colour. It appears in a number of scattered points on an area of about 10 km^2 which are both abandoned and active quarry, breakdown zone of lava flows and near the principal volcanic centres.

The biggest outcrop of this horizon is just south of Los Helechos volcanic group, along a slope being part of a “relict” of the underlying Famara massif, where a large active quarry occurs on the village of Maguez. Here the dark pyroclastic material is covered by the lava flows of Los Helechos that are interested by inflation processes testified by dome-like shape of pahoehoe lava sheets (fig. 4.14).

Figure 4.14. Deformation of lava flows because of the inflation on the quarry of Maguez.

From our observations on this quarry, we have supposed, for this layer, a thickness of 10-20 metres and an average attitude of 180°/15° and 136°/19° but upward the inclination seemed to be higher by eye, suggesting a deposition over a pre-existent paleotopography.

Figure 4.15. Lapilli horizon covering the entire slope on the quarry of Maguez.

A number of smaller abandoned quarries appear at the bottom of La Corona, south and east of the cone, and once again the lava flows have stood over the level of lapilli.

Inside one of these quarries, we have observed an outcrop of fractured and altered basalts (fig. 4.16) and just above them, we have found a bed with caliche and basaltic fragments (fig 4.17): the combination of this factors let us to state that these basalts have been exposed for a long period before being buried by the pyroclastic materials.

This outcrop is directly covered by the lapilli horizon that fills the quarry.

Figure 4.16. The altered and fractured basalts outcropping inside the quarry.

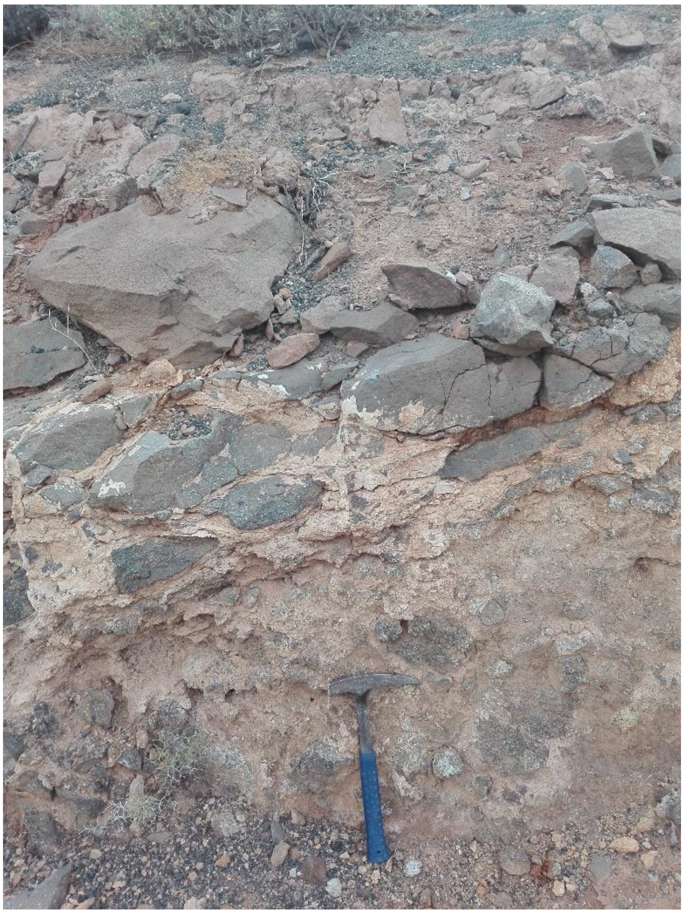

Figure 4.17. Caliche and basaltic fragments.

In all the quarries at the bottom of La Corona, it has been hard to take the orientation of lapilli layers but we have been able to state that they have followed the pre-existent underlying topography (fig. 4.18). Furthermore, we have seen that the thickness of the pyroclastic materials seemed to be lower than Los Helechos' neighbourhoods, estimating a value up to 6-7 metres (fig. 4.19).

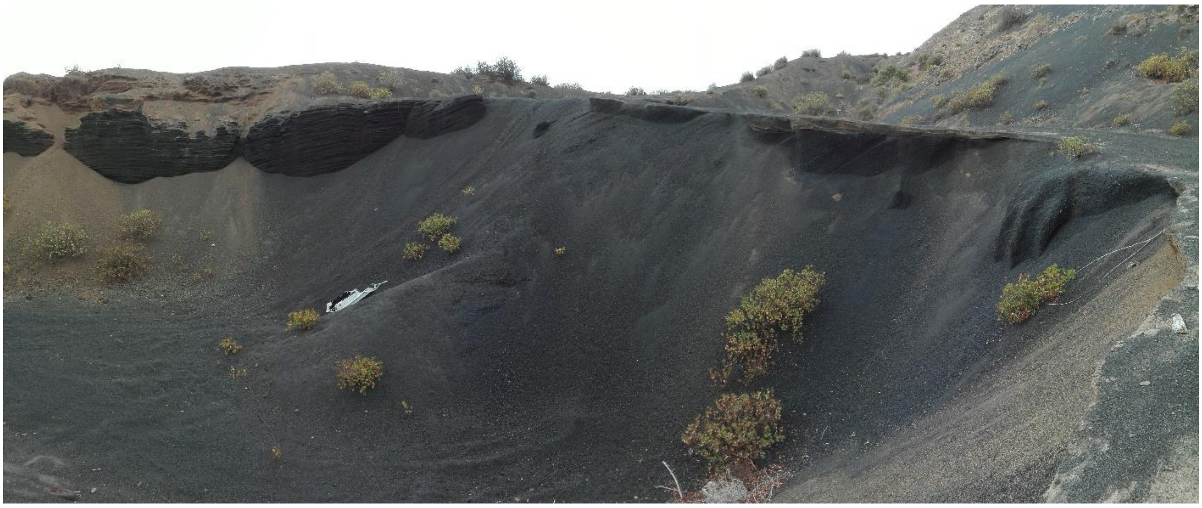

Figure 4.18. Lapilly horizon with different attitude that covered the paleotopography.

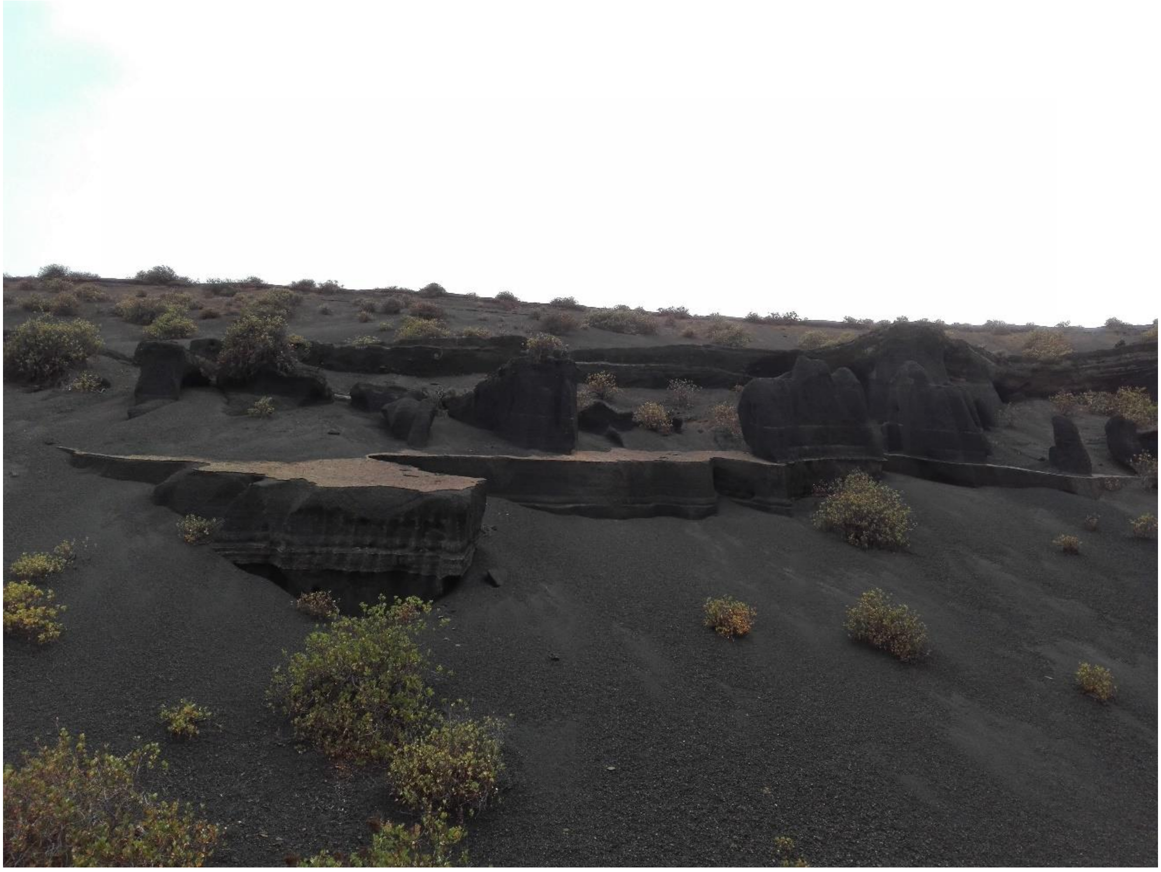

Figure 4.19. Thick beds of lapilli.

Just downhill, along the street LZ-201 that connects the villages of Arrieta and Yé (fig. 4.20), we have noted a series of breakdowns that enable to see the contact between the pyroclastic deposits and lava flows of La Corona (fig 4.21 a and b): these breakdowns might be due to the inability of the incoherent level of lapilli to sustain the overlying lava flows.

Figure 4.20. Google Earth view showing the location of the breakdowns sites.

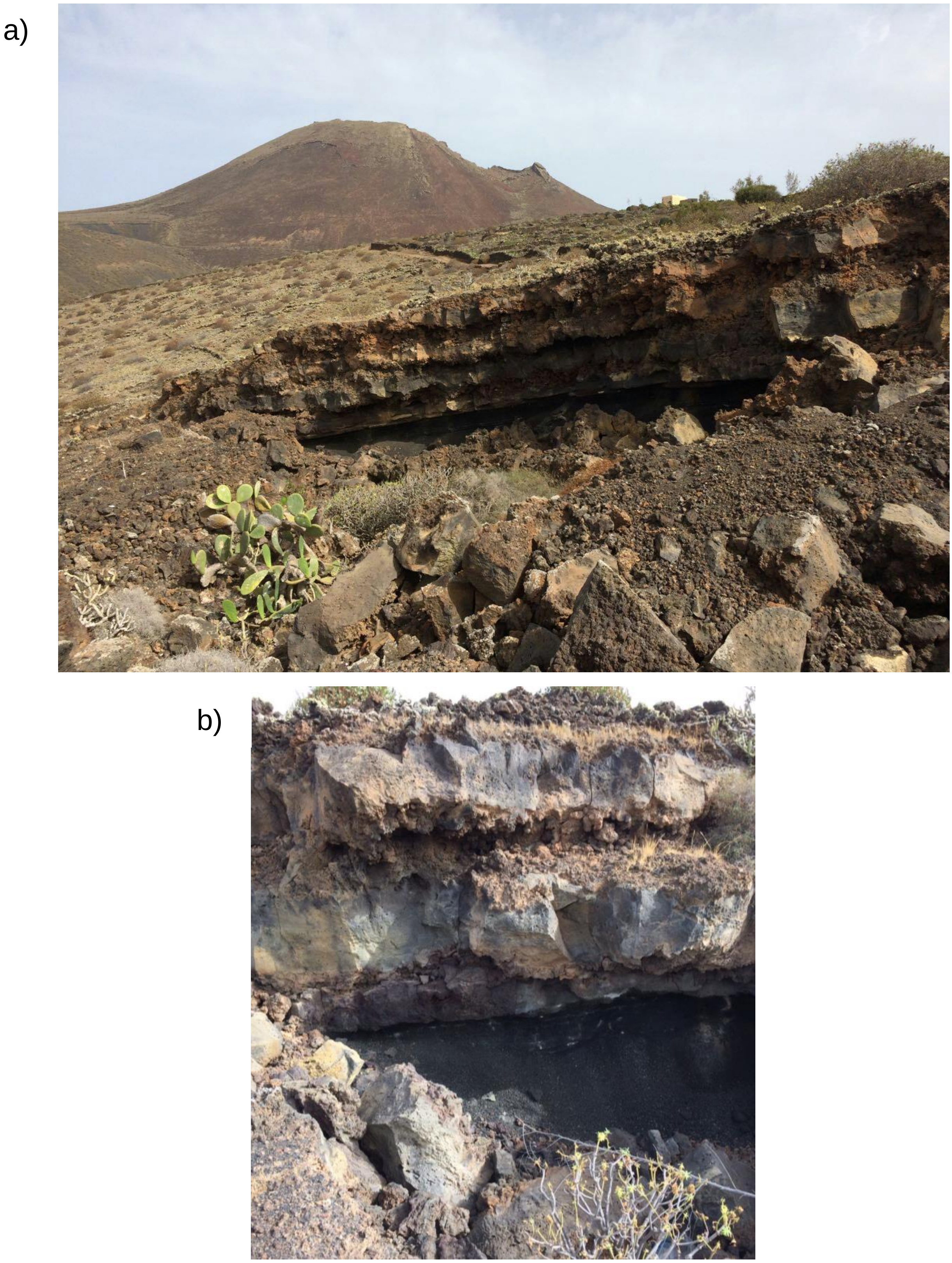

Figure 4.21. a) Breakdown and La Corona volcano. b) The contact between the lapilli layer and the lava flows of La Corona.

Following the same street but on the western side of La Corona, the lapilli layer abundantly outcrops overlying a caliche horizon that it seems a continuum of the soil observed just north on the top surface of the Famara massif (fig. 4.22). This contact has led us to state that the lapilli horizon lies directly over the complex of Famara.

Figure 4.22. Lapilli horizon overlying a level of caliche west of La Corona.

Also near La Quemada we have noted a couple of small abandoned quarries, one at the bottom of its southwestern flank (fig. 4.23) and another one 500 metres further south from the volcanic cone (fig. 4.24). In each of these depressions lava flows of La Corona overhung the lapilli horizon that here does not exceed the thickness of 4-5 metres.

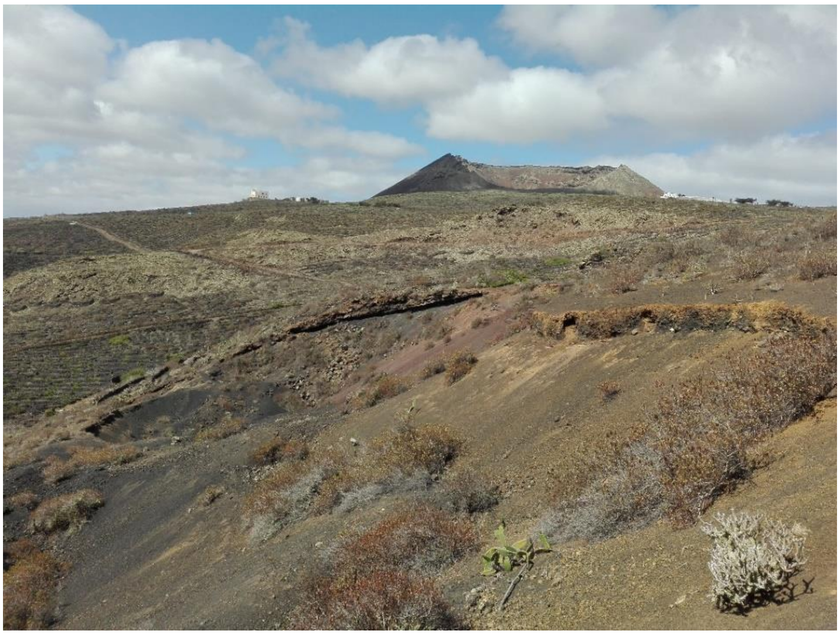

Figure 4.23. The quarry at the bottom of the southwestern side of La Quemada. La Corona in the background.

Figure 4.24. Contact between the lapilli layer and the lava flows of La Corona near La Quemada.

According to our observations of lapilli horizon, we have stated that this pyroclastic event has probably placed between Famara complex and the Quaternary volcanic complexes, by covering the paleotopography defined by the Famara massif.

The issue centre of this pyroclastic material is difficult to determine but taking account into the thickness decreasing from Los Helechos to La Quemada, it is possible that the first one it could have been the main origin point. The grain size of lapilli is more or less the same in all the quarries, ranging from 0,5 to 3 centimetres.

4.1.3 QUATERNARY VOLCANIC COMPLEX

This complex is formed, from SW to NE, of three aligned emission centres, Los Helechos, in turn made of three adjacent cones (La Quemada de Maguez, Los Helechos, La Cerca), La Corona and La Quemada, and their lava fields.

Even though the Quaternary lava flows cover most of the studied area, in terms of outdoor fieldwork, our activity on this volcanic system has been rather limited to the detection of some lava flow fronts and to the edifices of La Corona and La Quemada. In fact, our purpose about the Quaternary volcanism has been the study of the lava tube of La Corona, leaving on the background the detailed description of the lava flows by simply surveying them from the craters of La Corona and La Quemada and carrying out local field checks of the map obtained through remote sensing interpretation.

The pyroclastic cones of this NE-SW alignment are mostly formed of pyroclastic products ranging from ashes to bombs issued during the initial stages of their activities and following lava flows. We have observed that all these volcanic cones, as others in Lanzarote, collapsed along their eastern or northern flanks. This occurs because the trade winds blowing from NE to SW aid the deposition of pyroclastic materials along the southern and western sides of the cones reinforcing them whereas the eastern and northern sides weakened and collapsed through time.

La Corona is a 609 metres-high volcanic cone with a diameter of about 1.5 km. The ascent to the crater occurs along the northern side that is partially collapsed (fig. 4.25), providing a preferential way for many lava flows, among which those generating a huge lavafall along the Famara cliff (fig. 4.26). This lavafall covers the entire slope from a height of 350 metres to the coastline and in the distal portion it develops some small partially-formed overcrusted lava tubes (fig. 4.27).

Figure 4.25. La Corona with its collapsed flank facing to the north.

Figure 4.26. Lava fall of La Corona covering the western side of the Famara cliff.

Figure 4.27. Termination of the lava tube occurring in the distal portion of the lava fall.

The inner of the crater of La Corona (fig. 4.28) is filled by reddish or purplish oxidized pyroclastic materials and lava blocks whereas the outer wall of the cone is commonly black and non-oxidized.

On the eastern edge of the crater there is a small vent that most likely has fed other lava flows. Another secondary vent occurs at the base of the same slope and since it is very close to the first skylights of the lava tube (fig. 4.29), we have suggested that it could have been the spreading centres of the lava flows that have given rise to this volcanic cave.

Around the crater and at the top of the inner side of the volcano, there is a lava crown that originated from lava fountains or which is the remnant of lava flows.

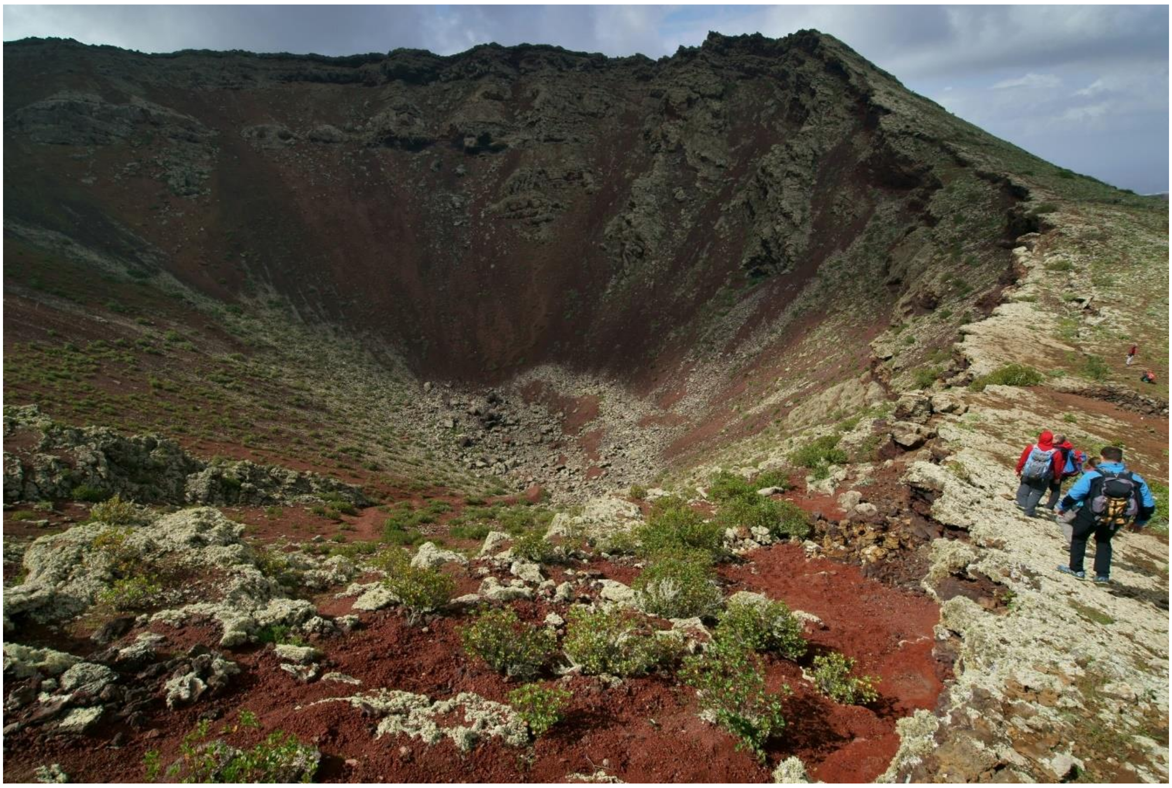

Figure 4.28. The crater of La Corona with red oxidized pyroclasts and lava flows covering the rim. Credits: Robbie Shone.

Figure 4.29. View from the lateral vent from which it is possible to see the first skylights of the lava tube of La Corona.

La Quemada is a 356 metres-high and 800 metres-wide volcanic cone showing a huge fracture on the eastern side, from which the lava flows could get out (fig 4.30). The lava flows of this volcano poorly outcrop because they have almost completely been covered by the more recent flows of La Corona.

Figure 4.30. The fracture on the eastern side of La Quemada observed from the rim crater.

4.2 CAVE-IN FIELDWORK

This part of our fieldwork activity has been dedicated to the survey of a segment of the lava tube of La Corona and it has been one of the most important steps of our work, since the inner walls of the lava tube might show the cross-section view of the different volcanic events that have characterised this part of Lanzarote. In this way we have been able both to reconstruct the geological history and to verify whether some features are the same visible externally (and vice versa) or not.

Altogether this conduct is 7.6 km long, whose last 1.6 km are below sea level but according to our aim we have surveyed only a segment belonging to the terrestrial part. The 6 km long terrestrial portion of the tube is shown on the surface thanks to a number of skylights or, in the local language, “jameos” that enable to track the pathway of the cave.

Above the entrances of the lava tube it is possible to individuate the lava flows that form the roof of the cave and we have counted several lava flows which in some jameos have been at least ten. This is the result of the inflation mechanism, demonstrating that the lava tube of La Corona has formed through this process (fig. 4.31).

Figure 4.31. Lava flows stack above the entrance of the Jameo de la Puerta Falsa: this feature suggests the formation of the lava tube by inflation as stated by Kempe (2010).

From La Corona to the coastline there are twenty jameos (not everyone has a name) that reveal the path of the lava tube and whose distribution is not regular. The first eight jameos are situated near the volcanic cone of La Corona, among which there are the Jameo de Arriba, the Jameo de La Corona, the three Jameos de los Lajares and the Jameo Largo (fig. 4.32). Just downstream there are two close jameos, among which the Jameo de Prendes. Another group of five jameos is located further downstream and includes the Jameo de la Gente, Jameo Tacho, Jameo Cumplido, Jameo Agujerado and Jameo de la Puerta Falsa (fig. 4.33).

Closer to the coastline there are the Cueva de los Verdes and the group of Jameos del Agua (fig. 4.34). The Jameo de Prendes is directly connected with the Cueva de los Verdes and this segment of the lava tube is known as Cueva de los Verdes system, that can be divided into three segments (Montoriol-Pous and De Mier, 1969): Jameo de Prendes – Jameo de la Gente (1170 metres long), Jameo de la Gente – Jameo de la Puerta Falsa (1165 metres long) and Jameo de la Puerta Falsa – Cueva de los Verdes (1370 metres long).

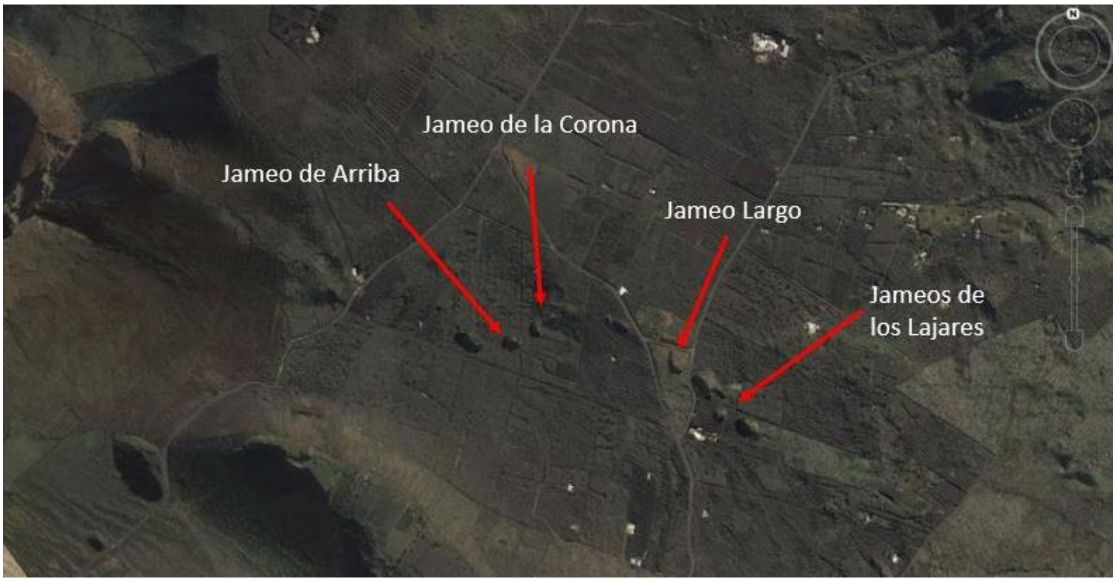

Figure 4.32. Google Earth view of the first eight jameos.

Figure 4.33. Google Earth view of the system of Cueva de los Verdes.

Figure 4.34. Google Earth view of the system of the Jameos del Agua.

The first eight jameos do not provide an access to the cave but since they are both located more or less at the same altitude of the quarries at the bottom of La Corona in which we have seen the lapilli layer and close to them, we have checked whether on the wall of these jameos this horizon occurs or not.

Only inside the first of the Jameos de los Lajares we have individuated a reddish level of ashes and lapilli that surfaced between the wall and the floor of the skylight with an attitude of 180°/20°. We have not been able to identify the pyroclastic material inside the neighbours jameos and we have supposed that it occurs below the filling rockfalls or inside the underlying lava tube.

The Jameo de Prendes provides an access to the tube, both up- and downstream, and getting into the lava tube toward upstream, on the left we have recognized the pyroclastic level between the lava flows of the wall, lying very close to the floor.

We have measured the attitude of the basalts just above this layer that was of 120°/15° and 90°/15°. Soon after the downstream entrance, we have noted the same level of lapilli and ashes once again next to the floor with an attitude of 265°/11° that is almost opposite to the previous one: this irregularity suggests that this pyroclastic layer could have covered a paleotopography characterized by ravines and valleys downgrading toward the east.

The continuation through the lava tube has immediately been prevented upstream by the rockfall filling the entire section (fig. 4.35) of the tube and downstream by a vertical step.

Above the upstream entrance, we have noted in cross section a lavafall filling an underneath level of the lava tube (fig. 4.36).

Figure 4.35. Rockfall filling the section near entrance of the Jameo de Prendes.

Figure 4.36. Lavafall filling an underneath level of the lava tube above the entrance of the Jameo de Prendes. Credits: Norma Damiano.

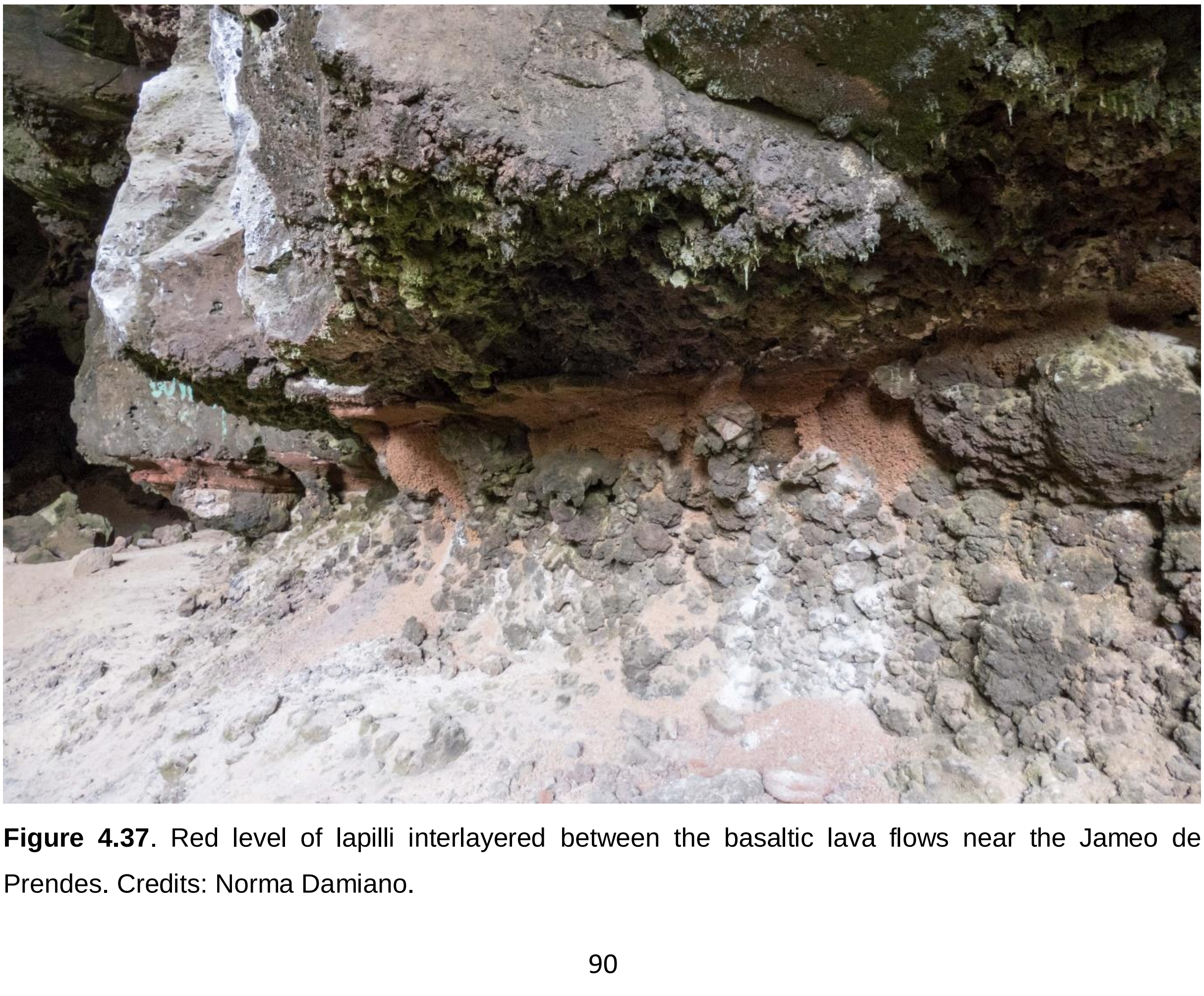

Figure 4.37. Red level of lapilli interlayered between the basaltic lava flows near the Jameo de Prendes. Credits: Norma Damiano.

From the Jameo de la Gente it is possible to walk down the tube for long distances both up- and downstream. Along the upstream portion that leads to the Jameo de Prendes we have observed the reddish pyroclastic level (fig. 4.38) running on the walls and reaching a thickness up to two metres: after almost one kilometre we have arrived to a jump of several metres probably because of the presence of an underlying tunnel. In this part of the tube it seems that the lava flows underlying the pyroclastic layer are more fractured than those above.

Figure 4.38. Reddish level of lapilli inside the lava tube.

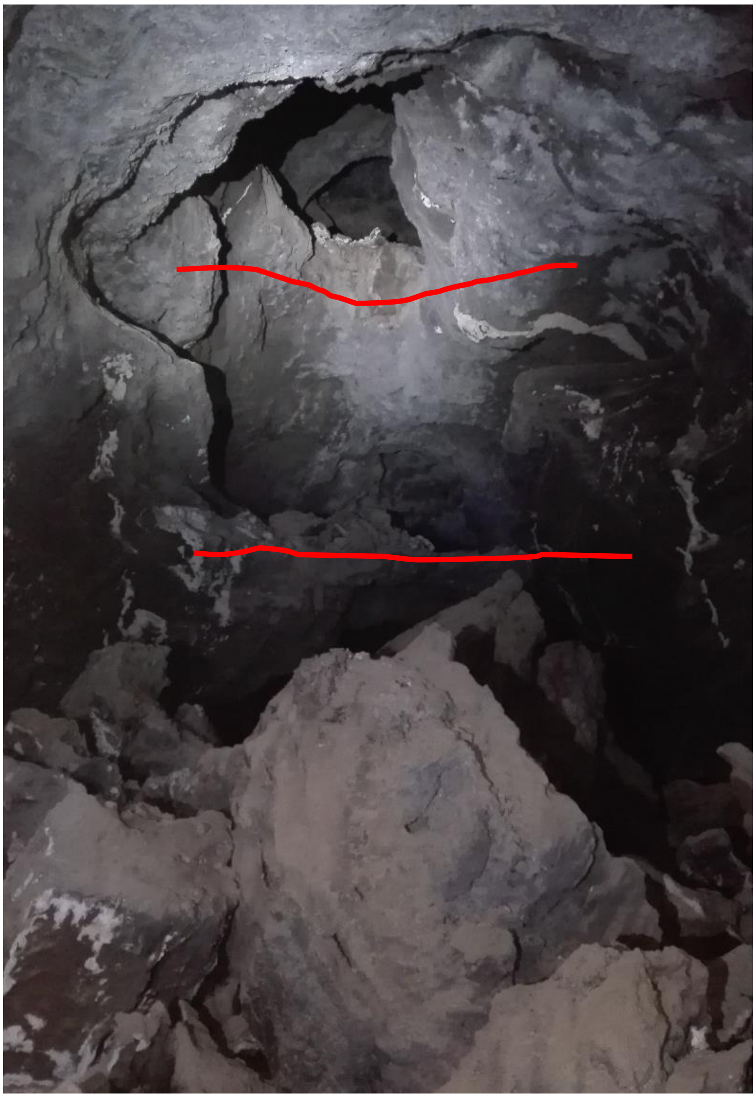

Figure 4.39. Section of the lava tube showing three superimposed levels just north of the Jameo de la Gente.

Also along the downstream track, toward the Jameo de la Puerta Falsa, we have noticed the red lapilli layer with some disruption due to lining lava flows that hid the original walls of the lava tube. In this portion, we have clearly observed that the lava flows below this level are not only fractured but often show an onion skin weathering (fig. 4.40). These features are characteristic of lava flows that have been affected by water weathering for a long time.

The thickness of the reddish layer ranged between 50 centimetres and 1 metre.

Figure 4.40. Onion skin weathering on the basalts below the red pyroclastic level.

At first, we have not reached the Jameo de la Puerta Falsa but afterwards we have walked down this segment upstream, going into through this jameo and getting out from the Jameo de la Gente. In this track, we have poorly observed the reddish pyroclastic level because of the widespread presence of lining lava. Just before reaching the Jameo de la Gente, the attitude of the pyroclastic material has been of 340°/10°. Between these two jameos, there are, from up- to downstream, the Jameo Tacho, the Jameo Cumplido and the Jameo Agujerado but we have not encountered them during our traversed from the Puerta Falsa to the Jameo de la Gente: this means that above the level that we have walked down there is at least another level from whose roof-breakdowns those three jameos have formed.

The reddish level of lapilli has been one of the most important features observed inside the lava tube and it seems to be an underground continuum of the lapilli complex described during the outdoor fieldwork. The only considerable difference hangs around in the colour: we suggest that this might be due to the alteration that results of enhanced oxidation due to the heating effect of the lava flows running through the tube.

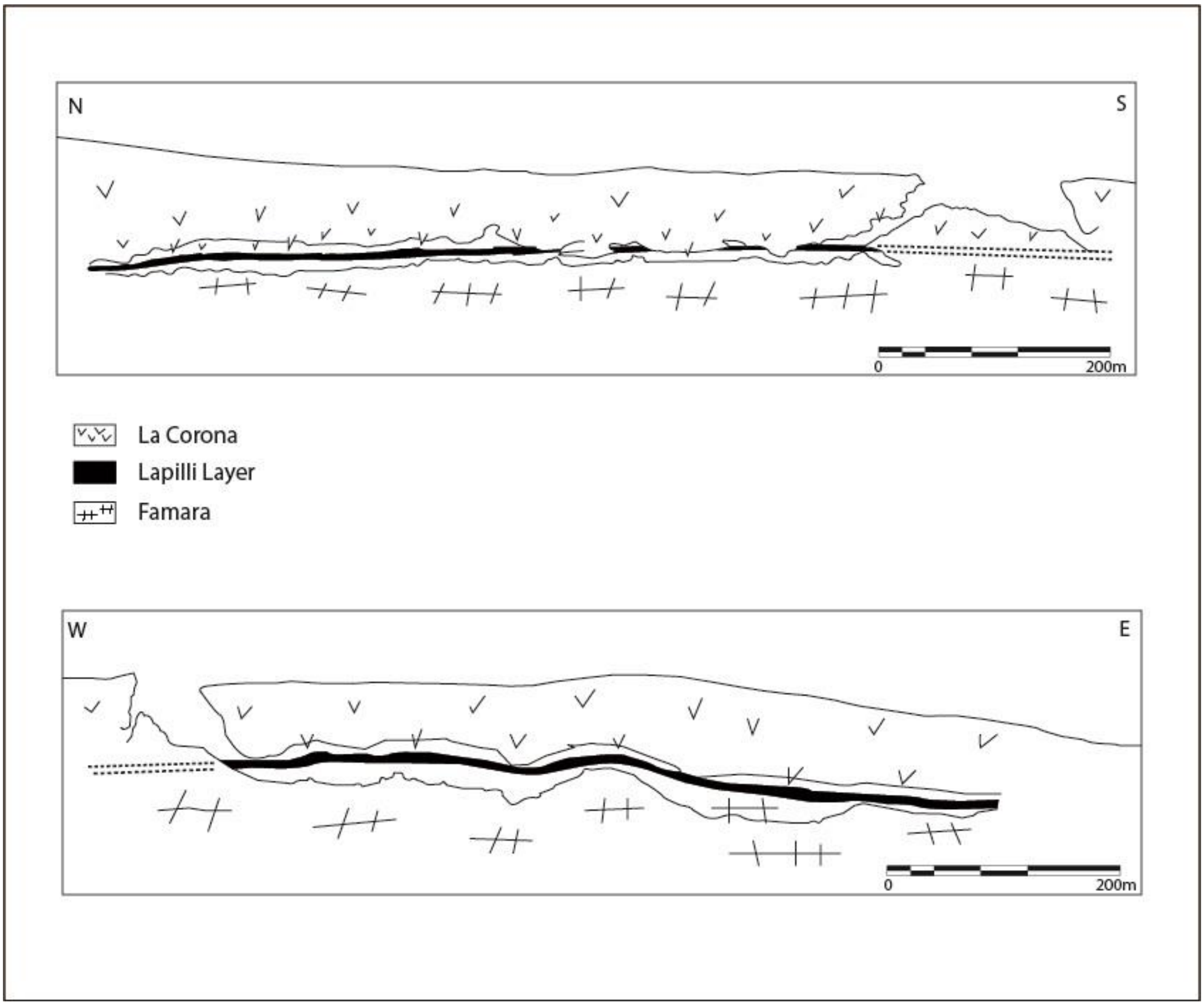

Figure 4.41. Conceptual scheme representing the lapilli horizon interlayered between two different volcanic events: the upper event is clearly made of the lava flows of La Corona and the lower one is probably made of the basaltic lava flows of the Famara complex, according to our interpretation.

4.2.1 LAVA TUBE MORFOLOGY

Thanks to the laser scanning survey, we have been able to obtain two tracks of the lava tube starting from the Jameo de la Gente, one upstream and the other one downstream, in order to get information about the path followed by the lava tube (fig. 4.42) and the variations of both longitudinal and cross sections.

Figure 4.42. Path of the lava tube of La Corona near the Jameo de la Gente.

The longitudinal sections (fig. 4.43) of the portion upstream of the jameo is about 900 metres long whereas the downstream portion is more or less 800 metres long.

These sections show that the downstream part has a more sinuous path than the upstream one that appear more flat and regular: furthermore, on the upstream part, between the point C and D, there is at least another level of the tube, confirming our observation displayed in the figure 4.39.

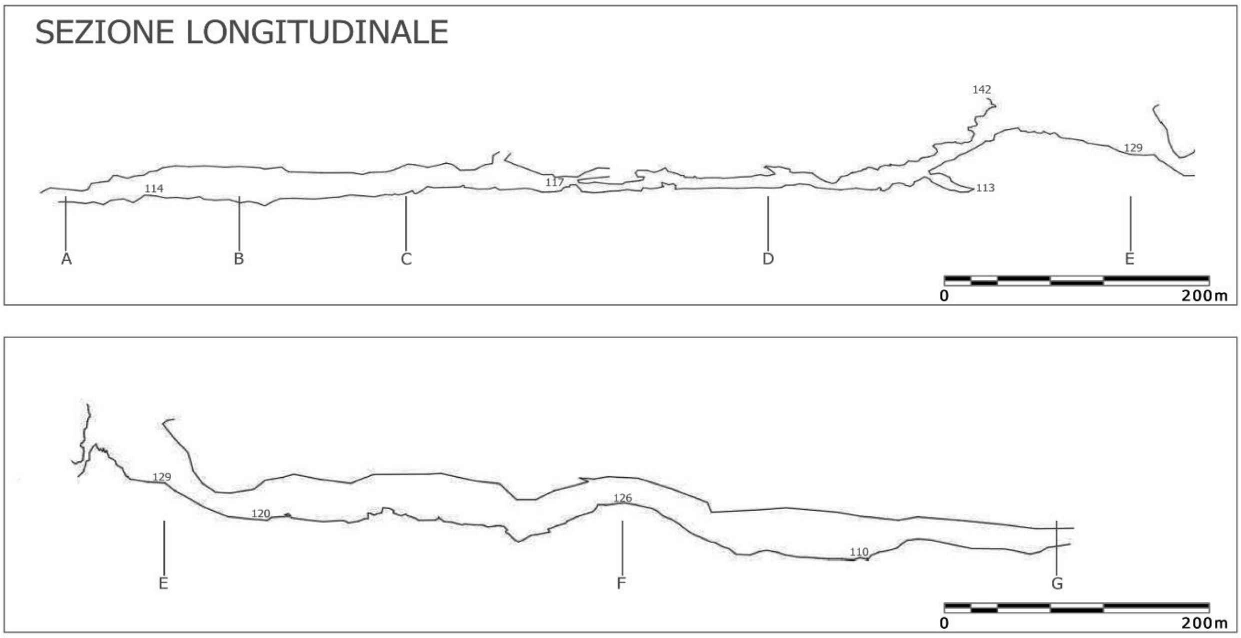

Figure 4.43. Longitudinal section of the lava tube north (above) and south (below) of the Jameo de la Gente.

The cross sections (fig. 4.44) display the variations of the shape of the tube section along the surveyed segment making it from narrow to wider and from higher to lower. Also from these sections it is possible to notice that in some points of the upstream portion (section 6 and 9), the lava tube has developed into two levels.

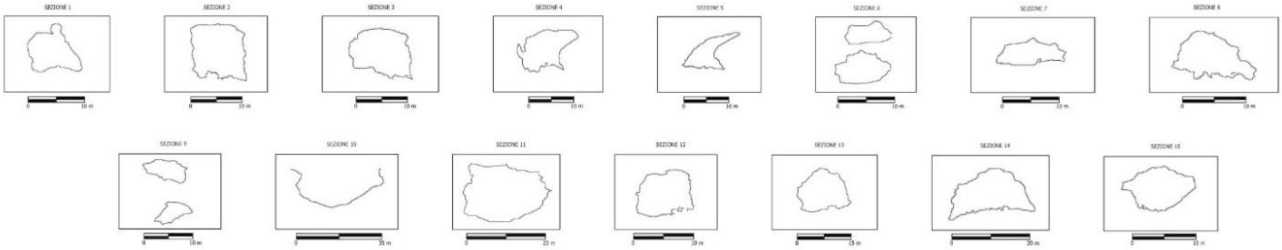

Figure 4.44. Cross sections of the entire segment of the lava tube near the Jameo de la Gente.

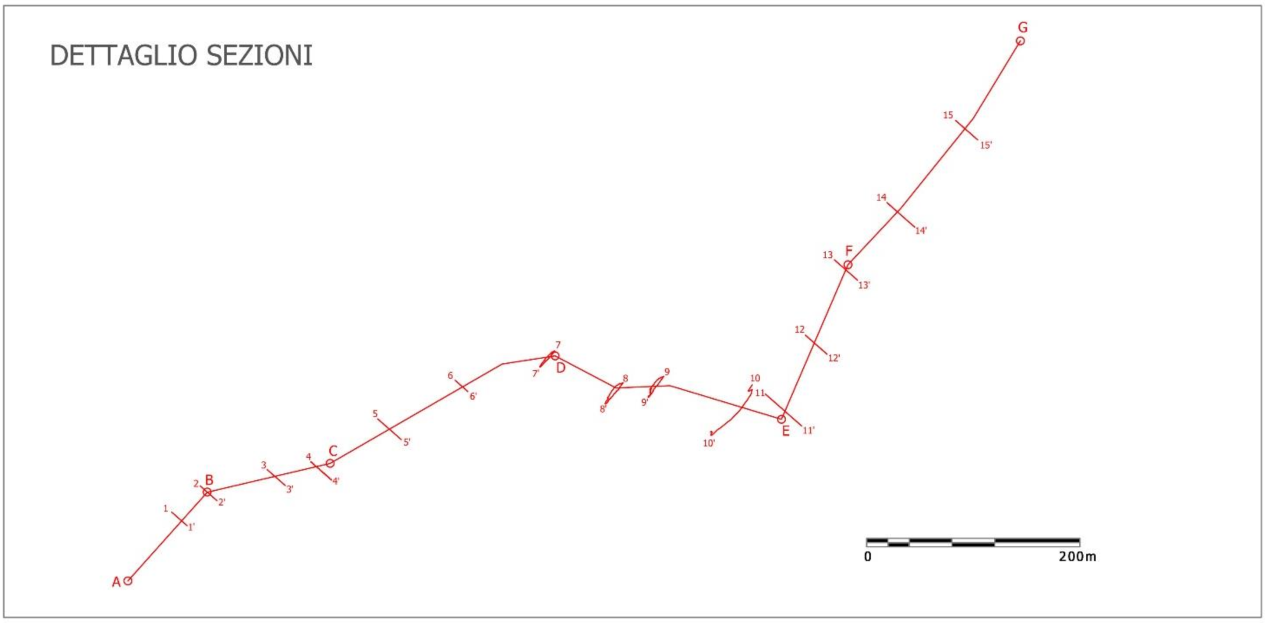

Figure 4.45. Scheme showing the positions of the different cross sections**.**

4.3 DESCRIPTION OF THE GEOLOGICAL MAP

The most important result of our fieldwork activity is the geological map of an almost 70 km^2 wide area, that includes\ the northern part of Lanzarote. We have divided the principal volcanic complexes of this area in different geological units according to our interpretation, as indicated on the legend of the map in the Annex.

The units of the complex of Famara are indicated with different shades of blue.

The lower unit (Famara 1) is indicated with a dark blue and is made of fractured and altered basaltic lava flows that poorly appear at the base of the Famara cliff, both on the eastern and western side. The soil 1 represented with the dark red, marks the boundary with the intermediate unit (Famara 2), indicated with the light blue: this unit is made of light pyroclastic deposits occurring in most of the western side of Famara where is crossed by a number of dykes but it outcrops on the eastern side only in its northernmost part.

The Soil 2 is represented with the yellow and consists of bioclastic sandstones and conglomerates that appear along the entire cliff. This soil represents the boundary between the intermediate and the upper unit of Famara. The upper unit (Famara 3) consists of basaltic lava flows divided by more or less continuous six soils (from Soil 3 to Soil 8) that distinguish seven substages (from Famara 3 to Famara 9): this unit is indicate through a lighter shade of blue and is the most widespread of the units of

Famara, covering most of the cliff and appearing in two points east of Los Helechos cones.

Inside the upper unit there are two lenses of pyroclastic deposits, indicated with an appropriate symbol, one on the southern part of the map at the top of the western Famara cliff and another one on the northern part across the median portion of the eastern cliff.

The unit named Lapilli Layer consists of dark unwelded lapilli and is indicated on the map with the dark green. This horizon appears in some scattered points at the bottom and centre of the map and in small expanses around La Corona volcano and at the bottom of the southern flanks of the Famara massif.

The unit called La Quemada, comprises the basaltic lava flows and the volcanic cone of La Quemada that appear in a very restricted zone located on the upper part of the map: it is represented through two shades of orange, one for the cone and the other one for the lava flows that spread toward the north.

The volcanic cones and basaltic lava flows of Los Helechos cover the entire lower part of the map and are represented by a purplish unit called Los Helechos: as for La Quemada unit, one shade highlights the three cones and another one the lava flows that expand toward the east and toward the west by means of a lava fall going down the Famara cliff.

The volcanic complex of La Corona comprises the central part of the map and represents the biggest lava spreading of the surveyed area (about 30 km^2). This unit (La Corona) is highlighted by three shades of green, one for the cone and two for the lava flows: in fact, according to our observations of lava flows fronts through the hillshade and slope raster in ArcGis, we have distinguished two phases of effusive activity of La Corona.

We have noted that there are zones in which fronts are less defined and hard to follow whereas in other zones there are well marked front. Our interpretation is that the lava flows with smoothed fronts are older than those with defined fronts as a result of the erosion. The lava flows of the first phase (Lava Flows 1) outcrop in an area next to the coastline exactly east of La Corona and La Quemada and in the zone where the lava tube is located (the path of the lava tube is indicated by the unit Lava Tube that highlights the jameos with the dark yellow). According to our statement, we have assumed that the effusive activity of this phase has been the responsible of the formation of the volcanic cave or alternatively that it has given the most important contribute. This first phase is indicated with the aquamarine colour.

The second phase of effusive activity (Lava Flows 2) is represented by the green colour and stands out the lava flows spreading toward the east-northeast, by covering the previous flows, the north and the west, by forming a lava fall running down the Famara cliff.

The soils and caliches that cover the flat upper surface of the Famara massif, are represented through the pale-yellow colour of the unit Soil/Caliche, appearing in the northern part of the map and west of the volcanic cone of La Corona.

The last unit to be represented has been called Colluvium and represents, with an appropriate symbol, the debris flows covering the western and eastern flanks of the Famara massif and all the other debris covering the base of the slopes.

The lineaments (Lineaments) highlight the crater rims of the volcanic cones and the edges of the quarries on the Lapilli Layer unit.

CHAPTER 5: RESULTS AND DISCUSSION

By combining the remote sensing and the classic fieldwork activity, we have been able to obtain a detailed geological map through which we have reconstructed the geological history of the surveyed area, introducing some interesting element.

5.1 THE FAMARA COMPLEX

As we have stated on the introduction of the geological setting the northern portion of Lanzarote has initially formed by the Famara shield-volcano, built up between the Miocene and the Pliocene through three distinctive stages of activity.

The lower unit, formed between 10.2 and 8.3 Ma (Carracedo and Rodriguez Badiola, 1993), is poorly represented in the northernmost part of the Famara massif, occurring in a few places at the base of the cliff to the west, the east and the north. It is made of fractured and altered basalts, often showing levels of caliche between flows stack.

The second and mainly the third units build up almost all the massif, outcropping more or less in a continuous manner except where covered by the quaternary colluvial deposits.

In particular the intermediate unit, built up between 6.7 and 5.3 Ma (Carracedo and Rodriguez Badiola, 1993), is made of light welded pyroclastic deposits, probably both fallout and cone-forming deposits and has been later intruded by dike swarms that are visible on the western cliff of Famara.

The upper unit, formed between 3.9 and 3.8 Ma (Carracedo and Rodriguez Badiola, 1993), is represented by stacked basaltic lava flows with a thickness that range from 150 to 350 metres intersected by a few levels of light pyroclastic materials.

Among the three units we have been able to recognize a series of reddish soils, thanks also to the support of the photogrammetric surveys, that highlights the activity gaps between the units and between sub-stages within them (fig. 4.5 and 4.10).

The first detected soil coincides with the boundary between the first and the second phase of volcanic activity and sometimes does not appear as a red marked level of sandstones or conglomerates but as a horizon of caliche and basaltic clasts.

A second important soil that occurs at the contact with the upper unit is the same observed in Valle Chico outcrop and represents a standstill period of about 500 Ka that led to the formation of an extensive sedimentary plain on the northern part of the Famara massif with a lot of terrestrial fossils (Lomoschitz et al., 2016).

We have found that other six soils characterise the third unit, some of them are continuous and detectable from side to side of the massif but others are interrupted or progressively joined together: this aspect points out as the effusive activity during the last phase has been discontinuous through space and time.

This can be seen by comparing the stratigraphic sections of figure 4.5 and 4.10 (fig. 5.1)

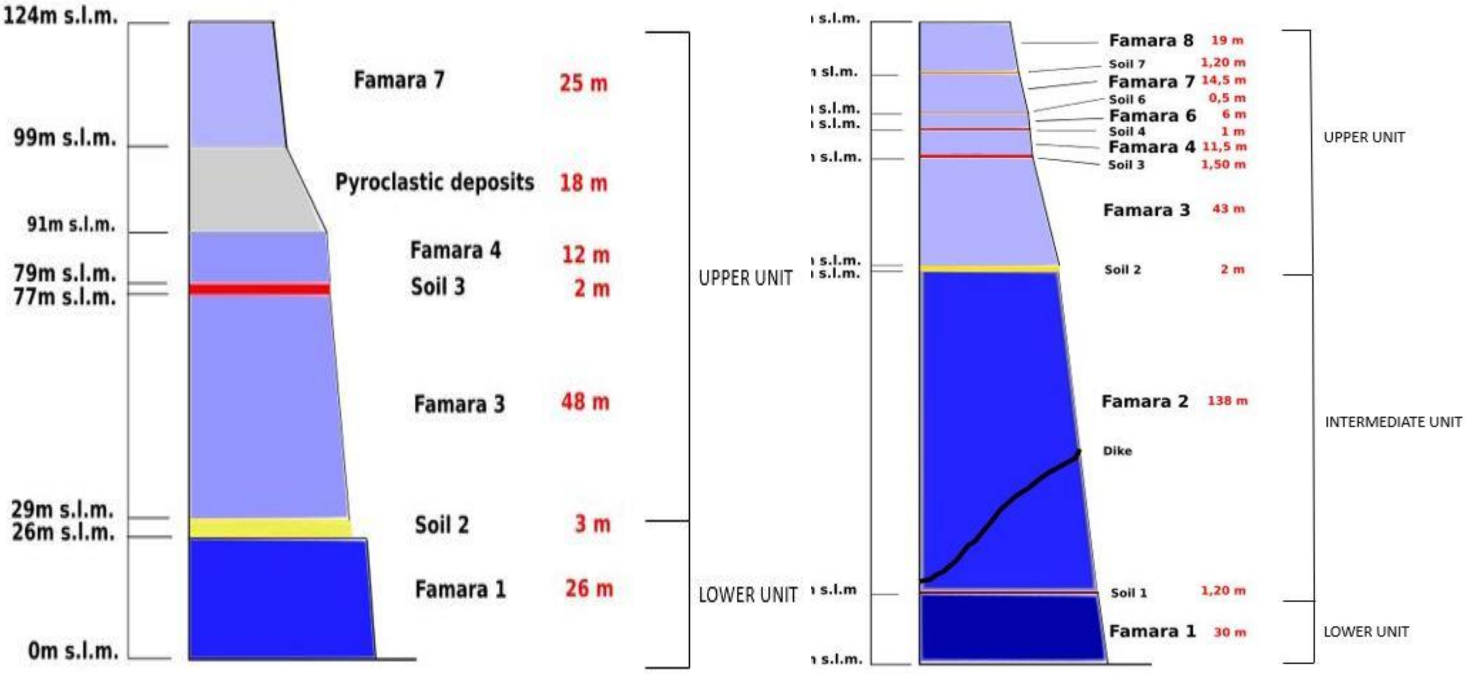

Figure 5.1. Correlating the two stratigraphic sections it is possible to check that not all the soils are continuous from the eastern to the western side.

The long period of exposure of the basaltic flows has given rise, at the top of the Famara massif, to a huge expanse of soil with many intercalations of caliche.

5.2 THE QUATERNARY VOLCANISM

After a long period of quiescence, the volcanic activity took back with fissure-type effusion of pyroclastic materials and abundant basaltic lava flows. The result was the formation of a NE-SW oriented alignment of scoria cones which produced a more than 40 km^2 wide lava field, hiding most of the eastern side of the Famara massif. The first spreading centre was La Quemada whose lava flows spread towards east and northeast. The second centre is represented by the Los Helechos group, made of three volcanic cones named La Quemada de Maguez, Los Helechos and La Cerca built up more or less 91 Ka ago. Typically, the activity associated to a scoria cone is composed by two phases: the initial stage of explosive activity that builds up the cone and the final stage during which lava flows issue from cones.

Schminke (2004) stated that the final deposits of the pyroclastic phase in many scoria cones are commonly black, well-sorted fallout lapilli, which can extend laterally for several kilometres: according to this argument and our fieldwork observations (thickness and grain size of the lapilli horizon), we have supposed that the observed lapilli layer has largely been produced by the group of Los Helechos and probably afterwards by La Corona and has mantled the paleotopography represented by the eroded and reshaped Famara massif.

The material involved during the formation of the scoria cones generally represents only a very small fraction of the total mass of erupted magma (Schminke, 2004). During the effusive stage, the lava flows of Los Helechos spread over a wide area by covering the lapilli layer and forming a lava flows field toward the east and a lava fall down the Famara cliff toward the west.

The last volcanic edifice of the alignment to be formed was the cone of La Corona around 21 ± 6.5 Ka ago and it is the highest among the volcanic centres of this group. Its activity has been more intense than other volcanic cones of Lanzarote and characterised by higher eruptive rates, as highlighted by the dimensions of the edifice and the magnitude of its lava flows field, the so-called “Malpaís de La Corona”.

The volcanic activity of La Corona started with an explosive phase that built up the cone through emission of pyroclastic materials followed by the emission of lava flows toward the north and the east by covering almost completely the flows of La Quemada and partially those of Los Helechos, and toward the west by forming an impressive lava fall down the cliff of Famara. According to our observations of the lava flows fronts through the hillshade and slope raster in ArcGis we have distinguished two phases of effusive activity of La Corona: in fact we have noted that there are zones in which the front are less defined and hard to follow whereas in other zones there are well marked fronts. Our interpretation is that the lava flows with smoothed fronts are older than those with defined fronts as a result of the erosion. The lava flows of the first phase outcrop in an area next to the coastline exactly east of La Corona and La Quemada and in the zone where the lava tube is located: for this reason, we assume that the effusive activity of this phase has been the responsible of the formation of the volcanic cave or alternatively that it has given the most important contribute.

The second phase of effusive activity is made of the lava flows spreading toward the east-northeast, by covering the previous flows, the north and the west, by forming a lava fall running down the Famara cliff. Also this phase may have contributed to the formation of the lava tube in the portion close to La Corona.

5.3 LAVA TUBE ORIGIN AND EVOLUTION

We have proposed a model for the formation and evolution of the lava tube of La Corona in the described geological scenario: this model is displayed in the picture 5.2.

Initially, the lava tube formed taking advantage of the discontinuity represented by the lapilli layer among the flows stack: in fact, this pyroclastic level could has behaved as a weakening zone that favoured the inflation mechanism of the lava flows with the formation of the lava tube (a). The continuous flowing of the lava streams inside the tube, caused the downcutting of the floor constituted by the basalts of the Famara complex and the consequent deepening of the tunnel (b). Afterwards, another level of the lava tube may have formed among the overlying lava flows (c). The downcutting occurred also in this new level until reaching the underneath level forming a unique huge lava tube (d). Once the flowing of lava streams inside the tube ceased, on the floor the accumulation of rockfalls deposits started to grow and on the walls some lava flows linings remained.

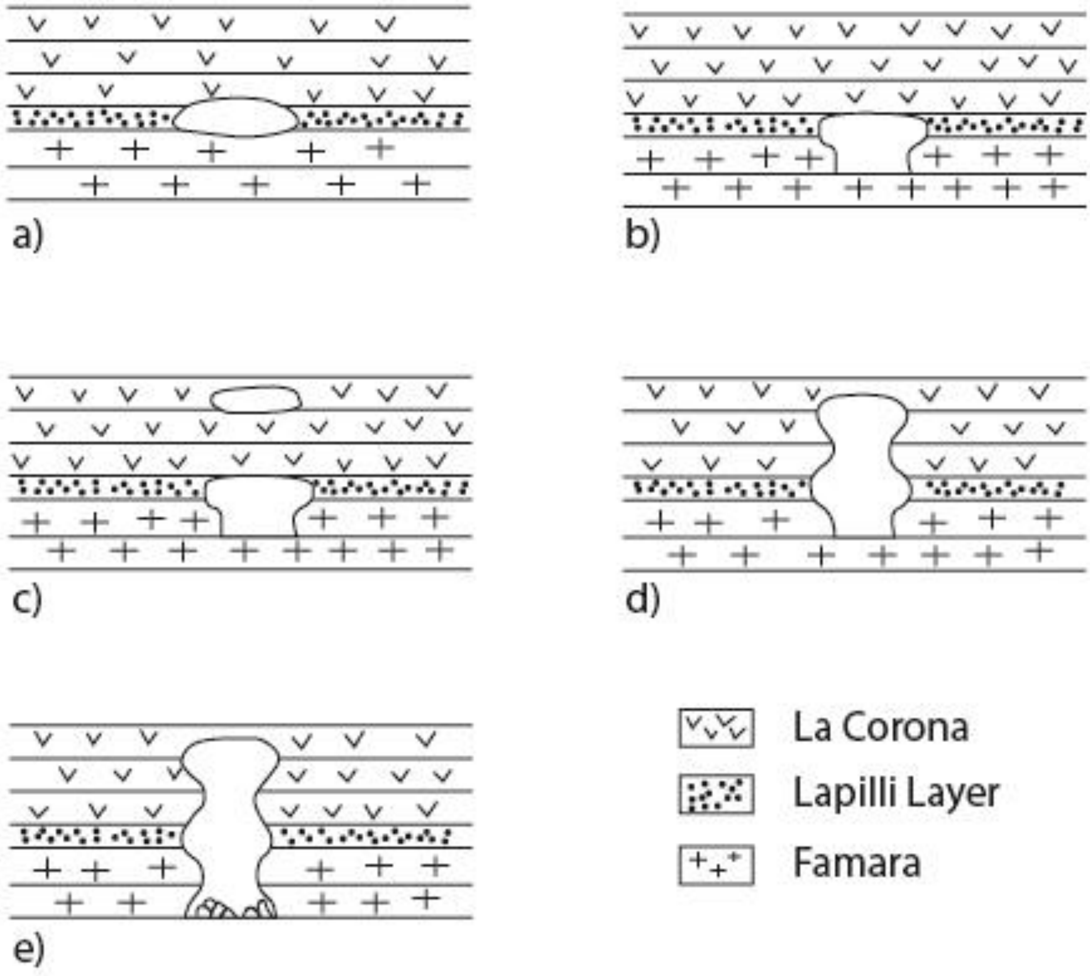

Figure 5.2. Schematic representation of the formation phases of the lava tube of La Corona according to our interpretation.

CHAPTER 6: CONCLUSIONS

The northernmost part of the island of Lanzarote has been affected by two distinct periods of volcanic activity, the first one that led to the building of the Famara complex between the Miocene and Pliocene, and the second one which caused the formation of the volcanic cones alignment of Los Helechos – La Corona – La Quemada and relative lava flows during the Quaternary. The Quaternary volcanism, whose lava flows cover most of the studied area, has been the most important recent volcanic event of the island, not including the historical eruptions of 1730 and 1824.

Through our work, we have provided a reconstruction of the turn of volcanic events that have interested this area since Miocene, dwelling on some aspects overlooked by previous authors, such as the volcanic sub-stages interleaved by soils on the Famara massif and the placement mechanism of the lava tube of La Corona in this context.

The conjunction of different geological survey techniques, from the classic fieldwork to the remote sensing analysis, such as photogrammetry, laser scanner and elaborations with geographic information systems (GIS), has allowed us to obtain a detailed geological map of a 70 km^2 wide area.

The most important volcanic feature of this area, and probably of the entire island, is the lava tube of La Corona that has been placed by inflation between the complex of Famara and the lava flows of this volcanic cone. These lava flows have progressively built up the volcanic cave through the inflation mechanism, which has been promoted by the interposed discontinuity between the two volcanic complexes represented by a layer of lapilli. Surveying the inner of the lava tube has been an important phase of our work that has allowed us to understand the relations among the outer and inner geological features, in particular as concerns the recognition of the lapilli horizon in and out the cave.

The photogrammetry has proved a powerful and important mean for the definition of all those elements that were difficult to check by fieldwork. The geological features that we have been able to recognize through 3D models have been the soils of Famara complex, the dikes, the La Corona’s lava fall and some boundaries among the geological units. In particular, we have recognized and tracked more soils intercalated to Famara sub-stages than displayed on previous works and geological maps.

Laser scanning has enabled to get the first 3D model of the lava tube of La Corona that is the starting point for detailed morphometric studies of this cave. Through this technique we have obtained the plan view track of the tube to be used on the geological map.

From our work, it appears that for the realization of a detailed geological map and for having an accurate understanding of the geologic setting of the investigated area, it is fundamental the combination of both fieldwork and remote sensing data.

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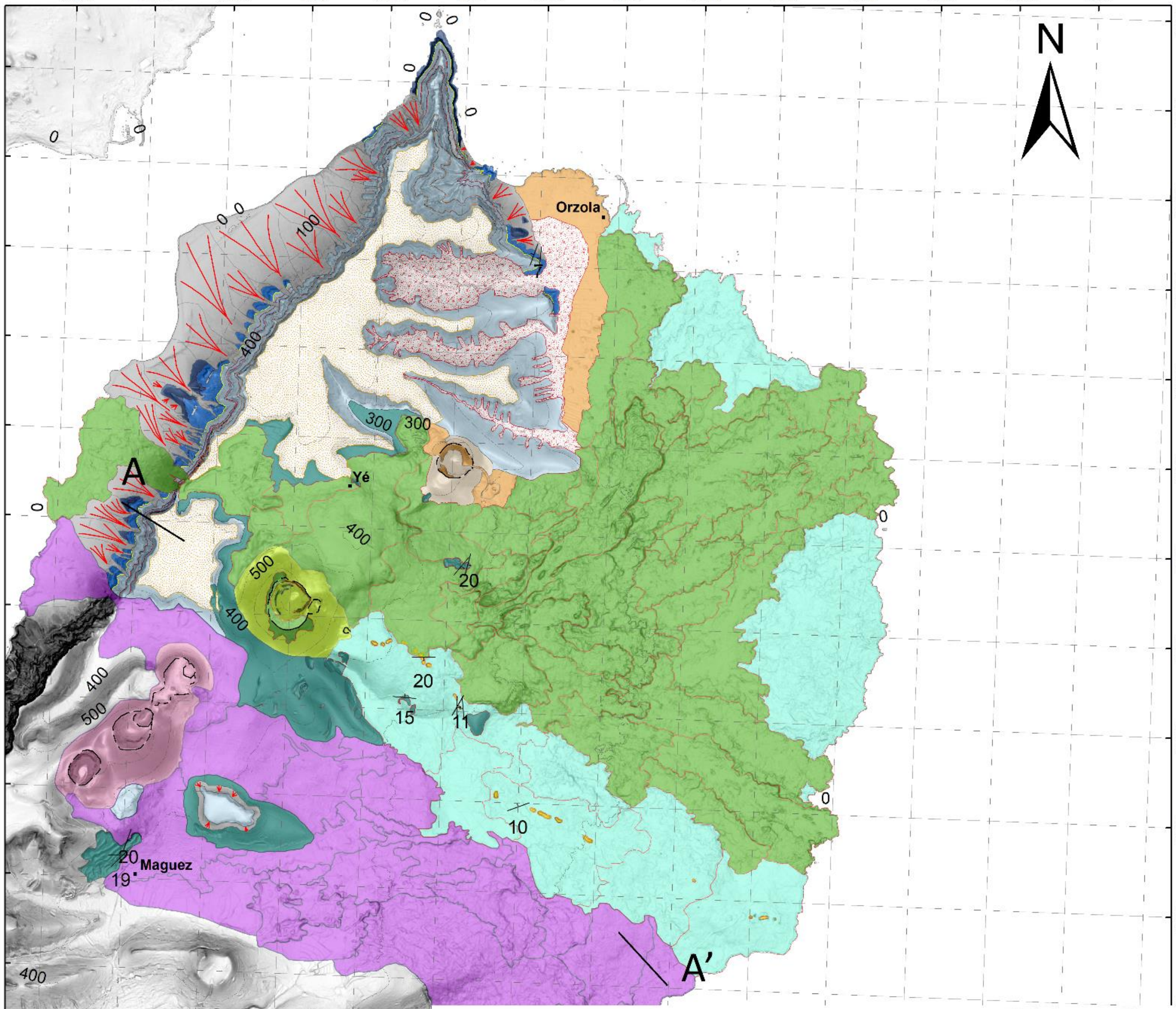
GEOLOGICAL MAP OF NORTH LANZAROTE

Authors: Matteo Tonello, Ilaria Tomasi.

SCALE 1:30.000



Legend

SYMBOLS

┤ Attitudes

LINEAMENTS

— Craters rim

COLLUVIUM

Debris Flow

Alluvial Deposits

LA CORONA

🟩 Lava Flows 2
🟨 Lava Tube
🟦 Lava Flows 1
🟩 Cone

Volcanic cones and relative basaltic lava flows. QUATERNARY

LOS HELECHOS

🟪 Lava Flows
🟪 Cones

Volcanic cones and relative basaltic lava flows. QUATERNARY

LA QUEMADA

🟧 Lava Flows
⬜ Cone

Volcanic cones and relative basaltic lava flows. QUATERNARY

LAPILLI LAYER

🟦 Lapilli — Dark unwelded lapilli. QUATERNARY

FAMARA

Soil/Caliche — Yellow to brown soils interlayered by caliche horizons. PLIOCENE

Famara 9
Soil 8
Famara 8
Soil 7
Famara 7
Soil 6
Famara 6
Soil 5
Pyroclastic deposits
Famara 5
Soil 4
Pyroclastic deposits
Famara 4
Soil 3
Famara 3

Basaltic lava flows with several interlayered soils of reddish sandstones and conglomerates. PLIOCENE

🟨 Soil 2 — Yellowish bioclastic sandstones and conglomerates. UPPER MIOCENE

Dikes
🟦 Famara 2

Light pyroclastic fallout deposits and scoria cones intruded by dikes. UPPER MIOCENE

Soil 1 — Reddish sandstones and conglomerates. UPPER MIOCENE

🟦 Famara 1 — Altered and fractured basaltic lava flows. UPPER MIOCENE

Geologic cross section