Sediment provenance from the coastal aeolian sands of La Graciosa Island (Canary Islands)

Alba Lucía Suárez Benítez

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Academic supervision by

Dr. José Mangas Viñuela

Dr. Inmaculada Menéndez González

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STUDENT: Alba Lucía Suárez Benítez

DEGREE: Degree in Oceanography

SUPERVISOR: José Mangas Viñuela

DEPARTMENT: Physics, Universidad de Las Palmas de Gran Canaria (ULPGC), Spain

INSTITUTION: Instituto Universitario de Oceanografía y Cambio Global (IOCAG)- Grupo Geología Aplicada y Regional (GEOGAR) ULPGC

SUPERVISOR: Inmaculada Menéndez González

DEPARTMENT: Physics, Universidad de Las Palmas de Gran Canaria (ULPGC), Spain

INSTITUTION: Instituto Universitario de Oceanografía y Cambio Global (IOCAG)- Grupo Geología Aplicada y Regional (GEOGAR) ULPGC

José Mangas Viñuela	Alba Lucía Suárez Benítez	Inmaculada Menéndez González
(Supervisor)	(Student)	(Supervisor)

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Abstract

La Graciosa Island has been formed by volcanic and sedimentary processes since the Middle Pleistocene. It is an island characterized by low-lying plains, with a notable alignment of volcanic cones oriented NE-SW (Montaña Bermeja, Morros Negros, Las Agujas Grande and Chica, El Mojón, and Montaña Amarilla). Nearly half of the island is covered by aeolian sands (*jables*) and muddy sediments of endorheic basins.

Field surveys have been carried out in the beach-dune systems of Las Conchas and Baja del Ganado in the NW of the island; Lambra beach and the jable of La Fragata in the N; Caletas beaches in the E; and Salado beach in the S. It has been observed that only the northern systems (Las Conchas and Lambra beaches) are currently active, while the others are semi-active (no marine sand enters and the existing sands are mobilized).

To understand the composition and relative abundance of the sand grains on La Graciosa, 21 thin sections of aeolian samples and 5 from endorheic basins were petrographically studied. They are associated with six beach-dune systems: Las Conchas, Baja del Ganado and Lambra beaches, and the jable of La Fragata in the northern sector, and Salado and Las Caletas beaches in the central-eastern sector. The petrographic results indicate that the most abundant sands are bioclastic in nature, with an average relative abundance of 77.5% ($\sigma = 8.6$). Among these, mollusk fauna remains dominate with 55%, while flora remains represented by detrital fragments of red coralline algae meshes—account for 22.5%. These are followed in abundance by terrigenous grains (volcanic rock and mineral fragments, and sedimentary intraclasts), reaching 22.5%. Of these, sedimentary intraclasts show an average of 14.5% ($\sigma = 5.9$), and volcanic terrigenous grains account for 8% ($\sigma = 1$). The bioclasts mainly originate from marine areas, while the lithoclasts come from the erosion of volcanic materials and sedimentary rocks found in both the rocky substrates of the intertidal zone and the surrounding supratidal areas. The endorheic sediments consist of sands and silts forming sedimentary intraclasts, with an average abundance of 98.5%.

The partial data on the abundance of the main components calculated in supratidal sands, foredune, nebkhas, and sandy sheet samples show slight variations within each beach-dune system studied and among the different beach-dune systems. These small differences are due to the location of the sample, the surrounding volcanic-sedimentary outcrops, and the presence of certain landforms. On the other hand, more notable differences have been observed in the composition and abundance data of the aeolian sands when comparing those studied on La Graciosa with those described in systems on other islands (Lanzarote, Fuerteventura, and Gran Canaria). Each system is influenced by its own local geological, geomorphological, and anthropogenic factors.

Keywords: Aeolian sands, beach-dune systems, La Graciosa, bioclastic sand, provenance analysis.

1. Introduction

La Graciosa, located to the north of Lanzarote, is part of the Chinijo Archipelago Natural Park, a protected area of great geological and ecological value in the Canary Islands. This group of islets includes Alegranza, Montaña Clara, the Roques del Este and del Oeste, and the Risco de Famara, with strict conservation measures in place to protect its biodiversity and geodiversity (Balcells et al., 2004; Galindo et al. 2019).

With an area of 27.05 km², La Graciosa is the only inhabited island, with 723 registered inhabitants in 2023 (INE, 2024). Its arid-dry climate features low rainfall, average temperatures ranging from 18 to 20°C, and high annual sunshine. The NNE winds, ranging from moderate to high intensity, influence sedimentary dynamics and vegetation distribution (Balcells et al., 2004; Pérez-Chacón et al., 2010). Its flora mainly consists of low, herbaceous xerophytic species, such as aulagas (*Launaea arborescens*), matos (Salsola), barrilla (*Mesembryanthemum crystallinum*), and tabaibas (Euphorbia), as well as psammophilic species adapted to sandy soils.

Historically, fishing and shellfishing were the economic backbone, but since the 1970s, tourism has become the primary source of income following state investment in infrastructure (Torres & Perdomo, 2016). This development has caused environmental issues, particularly regarding sedimentary dynamics.

The island faces a deficit of sand in its beach-dune systems, due to natural oceanographic processes and anthropogenic alterations. The low generation of bioclastic sands in marine bottoms, coupled with the action of marine currents, tides, and wind, affects the redistribution of sediments (Mangas et al., 2017). Additionally, tourist pressure and human intervention have accelerated erosion and affected dune stability (García-Romero et al., 2016; Santana-Cordero et al., 2016). To mitigate these impacts, the island of La Graciosa, the other islets of the Chinijo archipelago, and the cliffs of Famara were declared a Natural Park in 1986, a Marine Reserve in 1995, and together with the rest of the island of Lanzarote and its submerged environments were designated a Geopark by UNESCO in 2015. Thus, these figures of protection of natural and cultural heritage aim to balance economic development with of the ecosystems of these island territories.

The objectives of this study were to analyze the origin of windblown sands collected from various beach-dune systems on the island through their composition and abundance. The geomorphological variability of the sampling points, which includes supratidal zones, foredunes, nebkhas, sand sheets, endorheic soils, and aeolian areas with different vegetation densities, provided a broader perspective on sedimentary dynamics, potential sources, and sediment balances. Petrographic studies identified the terrigenous and bioclastic components of the samples, providing information about their origin and the geological, oceanographic, geographical and anthropogenic processes responsible for their transport and deposition on the island. The petrographic results of La Graciosa are also compared with other beach-dune systems of the eastern Canary Islands (Lanzarote, Fuerteventura, and Gran Canaria).

2. Geological setting

La Graciosa is of volcanic origin and presents a complex geology that reflects the evolution of volcanism and the sedimentary processes on this island (Fig. 1, De la Nuez Pestana et al., 1998; Balcells et al., 2004). It is separated from Lanzarote by the El Río strait, a marine channel about one kilometer wide and shallow, whose geomorphological characteristics have significantly influenced the sedimentary dynamics and coastal landscape configuration of the island (De la Nuez Pestana et al., 1998).

As shown in Figure 1, the geological formation of La Graciosa dates back to the Early Pleistocene, around 2.58 million years ago, when submarine volcanic activity led to the accumulation of pillow lavas and basaltic materials on the seafloor, forming a submarine platform (De la Nuez et al., 1997; Balcells et al., 2004). Subsequently, an increase in volcanic activity during the Middle-Upper Pleistocene (less than 0.8 Ma) generated strombolian and effusive eruptions, which deposited lava flows and pyroclasts on the pre-existing platform, contributing to the island's elevation (Morros Negros, La Fragata, Caletón del Pescado, etc.). This volcanic activity led to the alignment of volcanic cones with a predominant NE-SW orientation (Las Agujas, El Mojón, Montaña Amarilla, Montaña Bermeja, etc.), one of the island's most representative geological features (Balcells et al., 2004), with the highest point of the island at the top of the Aguja Grande volcano, reaching an elevation of 267 m (Fig. 1). Among the oldest materials on La Graciosa are the flows of Punta de la Herradura, Caleta del Sebo, and Baja del Corral, whose study allowed the identification of the basaltic platform from which its emergence began (De la Nuez Pestana et al., 1998).

Superficial geological processes have shaped the current morphology of La Graciosa. Erosion, sedimentation, and volcanic activity have led to the formation of sedimentary deposits such as aeolianites and paleosols, as well as coastal structures like beachrocks and marine terraces (Ortiz et al., 2006; Meco et al., 2006). Recent and current sedimentary processes associated with marine activity, surface waters, and wind have developed distinct deposits and morphologies such as those associated with the coast (sand and pebble beaches, rocky coasts, and cliffs), with surface waters channelled by ravines and slopes (different alluvial and colluvial deposits, and soils in endorheic areas), and with wind (various aeolian deposits: dunes and sand sheets).These morphologies and sedimentary deposits are located on platforms less than 80 m in elevation, inclined towards the sea (Fig. 1).

Currently, the island continues to experience intense sedimentary dynamics, with recent deposits of eolian sands (*Jable*, grey in Fig. 1, occupying almost half the island's surface) related to beach-dune systems distributed in two main sectors, to the north and south, separated by the alignment of volcanic cones (Balcells et al., 2004, Pérez-Chacón et al., 2010). These processes continue to shape the landscape and play a fundamental role in the island's geological evolution.

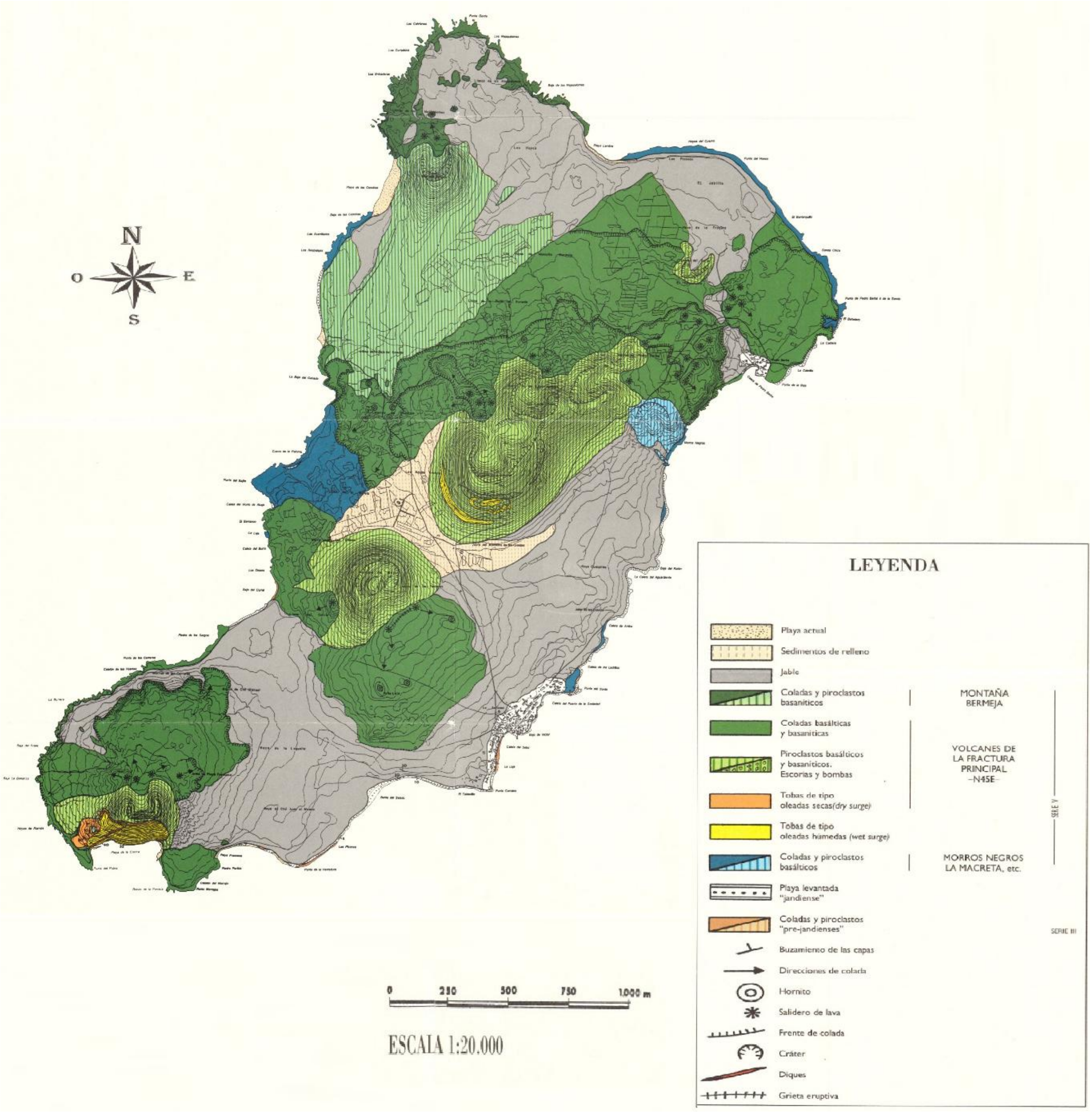

Figure 1. Geological map of La Graciosa Island. The main geological units are identified, including basaltic flows, volcanic cones, and recent sedimentary deposits. Source: De la Nuez Pestana et al. (1998).

3. Materials and methods

3.1. Sampling

The research project titled "Characterization of the Aeolian Sedimentary System of

La Graciosa (Canary Archipelago)" (Pérez-Chacón et al., 2010) was funded by the *Organismo Autónomo Parques Nacionales (Ministerio de Medio Ambiente y Medio Rural y Marino)* and the Fundación Universitaria de Las Palmas. Between May 2009 and July 2010, a total of 70 sand samples were collected, 26 of which were selected for the petrographic analysis presented in this research work (Fig. 2). The sampling was conducted by an interdisciplinary team of researchers from the University of Las Palmas de Gran Canaria, under the direction of RNDr. E. Pérez-Chacón Espino.

The sand samples were taken from diverse sedimentary environments across the island, including supratidal zones (foredunes, nebkhas, and sand sheets) and inland aeolian sand fields. In addition to the aeolian sands, volcanic rock samples (mainly Quaternary lavas) and sedimentary rocks such as beachrocks, paleosols, and eolianites were collected from coastal outcrops in this research project (although these samples are not the subject of study). These sandy samples provide a comprehensive representation of the island's recent aeolian sedimentary dynamics and its diversity.

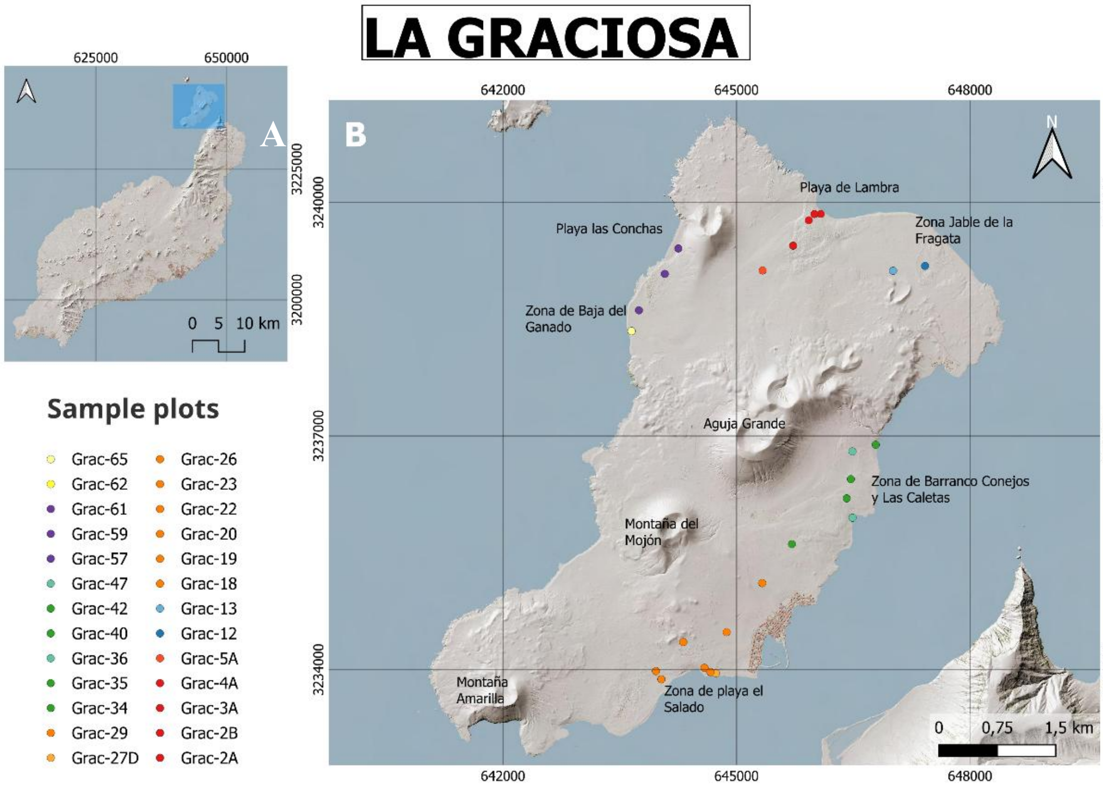

Figure 2. Study area. **A)** La Graciosa Island in light blue colour; **B)** Location of the analyzed samples in circles of different colours. Modified from *WMS LIDAR MTL,* provided by Grafcan (IDECanarias).

3.2. Studied beach–dune systems

The study focuses on the beach-dune systems of La Graciosa, which are divided into two main sectors: the northern system (Fig. 3) and the central-eastern system (Fig. 4). These systems are separated by a volcanic belt composed of Morros Negros, Morros de Pedro Barba, Las Agujas, and Montaña del Mojón, with a predominant NE-SW orientation (De la Nuez et al., 1997; Balcells et al., 2004). Each system exhibits distinct sedimentary dynamics influenced by oceanographic, geologic, aeolian, geomorphological, and anthropogenic factors.

3.2.1. North beach – dune systems

Four sedimentary environments have been identified: Las Conchas and Baja del Ganado (Fig. 3A), Lambra (Fig. 3B), and Jable de La Fragata (Fig. 3C). In these areas, sedimentary dynamics are influenced by the volcanic structures of Montaña Bermeja and Las Agujas, which control sand transport in two main directions: north-south (N-S) and east-west (E-W). Currently, the N-S axis is inactive due to the limited sand supply, although a change in environmental conditions could reactivate it. The interaction between aeolian transport and surface water erosion creates distinct sedimentary environments within this system: alluvial and colluvial zones, endorheic basin, etc (Menéndez et al., 2013).

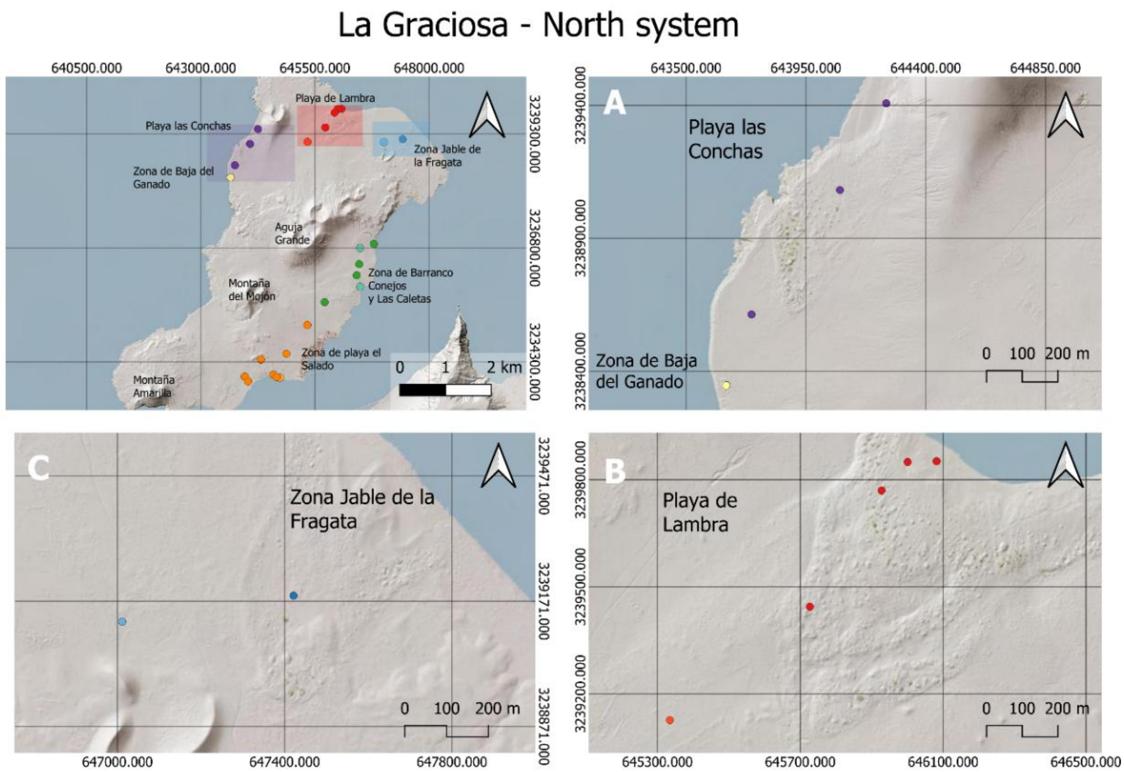

Figure 3. Geographic distribution of the northern beach-dune systems, with sampling points in the subsystems of **A)** Las Conchas and Baja del Ganado; **B)** Lambra and **C)** Jable de la Fragata. Modified from *WMS LIDAR MTL, provided by Grafcan (IDECanarias).*

- **Playa de Las Conchas**

The beach of Las Conchas, located in the northwest of the island (Figs. 3A and 5C), generates an active beach-dune system, with marine sands in the subtidal zone (sediments affected by waves, tides, and currents), the intertidal coastal area (sands affected mainly by waves and tides), and supratidal aeolian zone (detrital grains affected mainly by the wind). The deposits of supratidal aeolian sands, known as "*jable*" in the eastern Canary Islands, are oriented NE-SE in this area of Las Conchas, surrounded by Upper Pleistocene volcanic materials (the volcanic cone of Montaña Bermeja and the oldest lava platforms) (Figs. 1 and 2). The supratidal sands show morphologies as foredunes, nebkhas, and sand sheets, with ripples, wave-flow marks, and animal tracks as secondary aeolian structures.

To the southeast, aeolian sheets connect with an endorheic basin covered by dense vegetation, with snail shells and desiccation cracks. The materials rest on a basaltic flow, overlaid by biogenic carbonate beachrock and a reddish paleosol, all covered by a degrading coastal dune.

This area is the main detrital sediment input for La Graciosa, receiving sand from the north through a N-S transport axis, influenced by winds channeled by Montaña Bermeja. Seasonal variations in wave and tide energy create differences between winter and summer profiles, with sand deposits extending up to 50 meters (Pérez-Chacón et al., 2010).

- **Baja del Ganado**

The beach of Baja del Ganado, also located in the northwest of the island (Figs. 3A and 10B) features a beach–dune system that is not active, as the intertidal sands are only occasionally transported by wind to supratidal areas, where small nebkhas and sand sheets appear. In addition, the aeolian sands show the presence of detrital materials derived from nearby volcanic structures (volcanic cones of Las Agujas and Bermeja, lava flows, and pyroclastic fall deposits), and the pyroclasts are mobilized by sheet runoff. This process involves rainwater flowing over the surface, transporting fine particles.

This marks the end of sediment transport from the northern part of the island, culminating in a broad plain that forms an alluvial fan due to sediment accumulation by surface water. In this area, fine sediments accumulate, promoting the formation of small endorheic basins with moisture retention in the soil, supporting denser vegetation compared to other zones.

- **Playa Lambra**

The beach of Lambra, located in the north of La Graciosa (Figs. 3B, 5B and 10A), features a *jable* oriented NE-SW. Its intertidal zone contains loose sands that indicate the entry of sediment from subtidal sandy banks to intertidal areas, outcrops of volcanic lava flows, scattered accumulations of volcanic and sedimentary gravels, and a reddish-yellowish paleosol with mollusks fossils and insect traces.

Low cliffs consist of Upper Pleistocene basaltic flows, while orange aeolianites with terrestrial fossils emerge on the supratidal slope. Nebkhas and aeolian sheets with vegetation connect to an endorheic basin, where moisture supports dense vegetation and the formation of desiccation cracks. The system is shaped by the interaction of aeolian and marine processes, with more intense erosion in winter and sand deposition in summer. Northern trade winds during dry months maintain sediment transport, with Lambra being the only location in this system with a sandy beach.

- **Jable de La Fragata**

The rocky substrate of the coastal area of La Fragata is of volcanic nature and currently shows no sand input. In this area, a lava coastal platform is observed in the intertidal zone, with a winter step where the scoriaceous lava is covered by a conglomerate layer of paleobeach with shells of marine mollusks and a reddish matrix. In supratidal areas, an inactive fossil dune and areas of nebkhas and paleosols associated with endorheic basins appear (Fig. 3C). In addition, the detrital sediments with sparse vegetation show signs of water erosion related to small gullies, and the erosion has exposed the underlying substrate, particularly around specimens of *Traganum moquinii* and other plant species, whose roots have been exhumed.

This almost inactive *jable*, with a triangular morphology, is limited to the south by the volcanic cone of Lomo del Burro and its associated lava flows. It shows small nebkhas and thin sand sheets, partially stabilized by low vegetation, which show ripples and lee-side formations, indicating little active sediment transport.

3.2.2. Central - Eastern beach – dune systems

This Central–Eastern beach-dune system appears in the east-south of the island of La Graciosa and represents a long band of aeolian sands oriented in the NE-SW direction, bounded by the sea to the east and south, town and the port of Caleta del Sebo central-eastern, and the volcanic cones, lava flows, and pyroclastic deposits from the eruptions of Las Agujas and El Mojón to the West (Fig. 10C, D and E). Due to the large area it occupies, and the urbanization and port and road infrastructures of Caleta del Sebo, it has been divided into two beach-dune subsystems: Playa El Salado to the southwest (Fig. 4A), and Barranco Conejos and Las Caletas to the northeast (Fig. 4B).

Its dynamics are influenced by the aeolian sandy sediment input from the east coast and by volcanic formations to the west, which modify wind flow, slowing down detrital particles. A vegetation cover develops and stabilizes the sand sediment transport system. The thickness of the sand sheets, partially stabilized by vegetation, is only a few centimetres in this system and increases to several meters in the nebkhas.

The interaction between sediment supply and retention by volcanic topography and vegetation cover creates distinct environments (Fig. 10D). Currently, the system maintains a balance between dune stabilization and erosion, with surface runoff being the main process shaping the landscape.

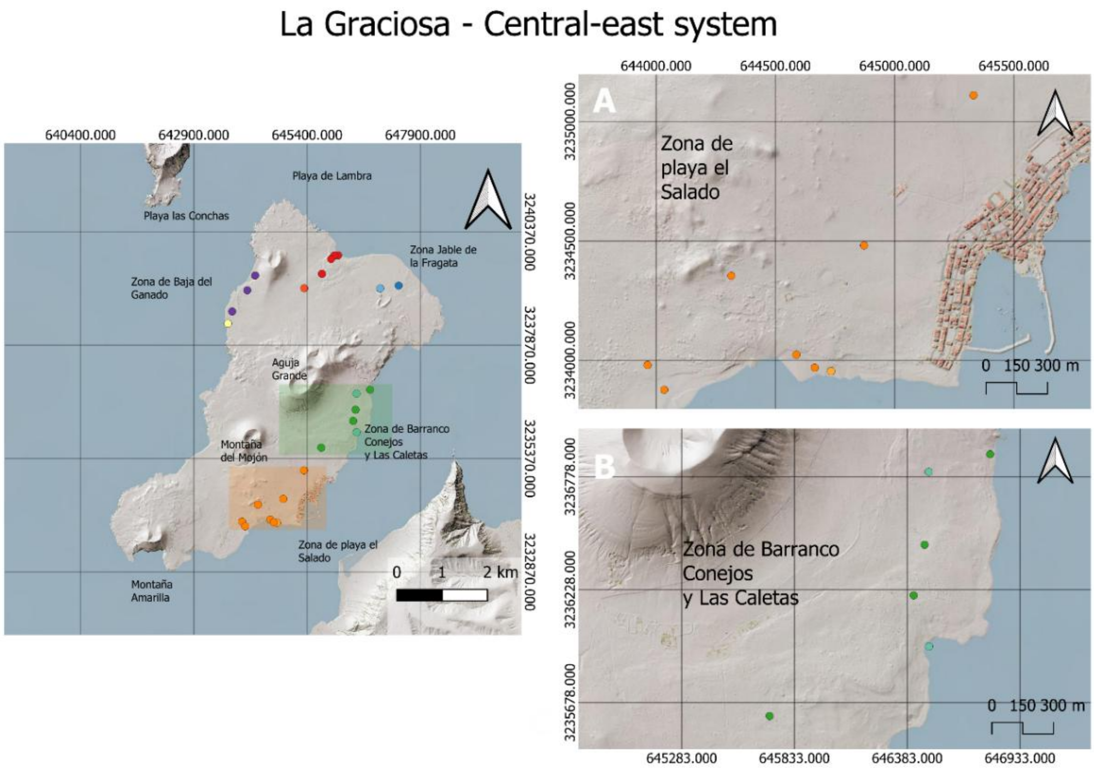

Figure 4. Geographic distribution of the central-eastern beach-dune system, with sampling points in the subsystems of Playa El Salado **A)** to the southeast, Barranco Conejos and Las Caletas; **B)** to the east of the island. Modified from *WMS LIDAR MTL, provided by Grafcan (IDECanarias).*

- **Playa El Salado**

Playa El Salado (Figs. 4A, 5A and 10F), located to the southeast, stretches in a SW-NE direction from the intertidal to the supratidal zones. A beachrock outcrop appears in the intertidal zone, composed of calcarenites and tilted toward the sea (Fig. 5A). A reddish-yellow paleosol with fossils of gastropods and hymenopteran ichnofossils lies on top of the beachrock, locally forming a small cliff of metric dimensions.

In addition, the intertidal area has discontinuous deposits of light-colored sands with terrestrial gastropod remains and sedimentary structures such as ripple marks and channels, covering rounded marine gravels of volcanic and sedimentary origin. In the supratidal zone, poorly cemented aeolianites with terrestrial gastropods and insect trace fossils appear, covered by current aeolian sands, forming a coastal dune (foredunes and nebkhas) and windblown sheets with sparse vegetation. On the western part of Salado beach, there is a cliff where deposits of calcarenites with large-angle cross-stratifications associated with Pleistocene paleodunes can be observed, which contain numerous rhizoliths (Fig. 10F).

The beach has received sand from both the interior aeolian system and coastal drift. However, the construction of port infrastructure at Caleta del Sebo and the increase in housing construction in the town have altered these processes (Pérez-Chacón et al., 2010 and 1012; Hernández-Calvento et al., 2013; García-Romero et al., 2016; Sanchéz-Cordero et al., 2016; Mangas et al., 2017), paralyzing the transport of sandy sediments north of the port and town, and reducing sand input to the south (Fig. 10E). Currently, erosion caused by marine dynamics (wave action, tides, and drift currents) is causing the beach to retreat, especially in the western coastal sector.

- **Barranco Conejos y Las Caletas**

The *jable* of Barranco de Los Conejos is located in the coastal area between the volcanic outcrops of Morros Negros and Baja del Ratón (Fig. 4B and 10C) and Caletas de Arriba and Abajo (Fig. 10D), formed by Upper-Middle Pleistocene basaltic flows and pyroclastic fall deposits. Current aeolian sands are deposited on these volcanic materials or on Upper Pleistocene aeolianites of cream colour and red paleosols, which contain terrestrial gastropod remains, hymenopteran ichnofossils, and volcanic fragments.

Figure 5. **A)** El Salado Beach; **B)** Lambra Beach; **C)** Las Conchas Beach and **D)** Baja del Ganado. On the beaches, the following features are identified: beachrock (1), paleosol (2), foredunes and nebkhas (3), and volcanic rock outcrops (4), present in different combinations depending on the location.

The intertidal zone we found sands in small bays, with a winter berm composed of basalt pebbles and blocks, and a rocky coast formed by outcrops of basalt flows predominates, constituting an irregular morphology with bays and capes, and observing scattered pebbles and blocks. Currently, there is no sand input from the intertidal zones to the supratidal areas. Near the beach are scarce coastal dunes on a gentle slope, followed by sparse nebkhas and windblown sheets with low-growing vegetation.

3.3. Petrographic microscope analysis

With the aim of identifying the different components present in the aeolian materials and quantifying their relative abundance, a total of 26 thin sections were prepared and petrographically analysed from samples collected at various study sites (Figs. 3 and 4). This allowed for the mineralogical and textural characterization of the main constituent grains (lithoclasts, bioclasts, and intraclasts) and the assessment of potential compositional variations between environments, in order to infer their provenance and sedimentary evolution.

The samples were prepared in specialized laboratories. At the Geology Laboratory of the University of Las Palmas de Gran Canaria, sand samples were quartered, as only about 20 grams were required. Subsequently, the detrital sediments were impregnated with transparent organic resins (EPOXY) at the General Rock Sample Preparation Service of the University of Salamanca to produce thin sections 20 microns thick, suitable for microscopic analysis (Fig. 6).

Figure 6. Images of the thin sections to which the petrographic study was carried out. In the right photograph, there is a thin section of sands and silts cemented with epoxy from an endorheic basin of Salado beach, La Graciosa, which were used for the petrographic study.

Petrographic analysis of the thin sections was carried out at the Geology Laboratory of the Physics Department of the University of Las Palmas de Gran Canaria, using a Leitz-ORTOPLAN polarizing microscope. Observations were made under polarized light with both parallel and crossed nicols, enabling the identification of optical and mineralogical properties of the components.

A point-counting system was applied to each thin section (200 points per sample), using an automated stepping stage (PETROG) in combination with PetrogLite software, which facilitated the classification and recording of 200 sand grains per sample. Each grain was assigned to a main group according to its nature: bioclasts, lithoclasts, or intraclasts (Table 1). This methodology allowed for the calculation of the relative abundance percentages of each component type (Annexes 1, 2 and 3).

Within the bioclast group, remains of algae, echinoderms, bryozoans, mollusks (calcitic and oxidized), and foraminifera (also calcitic and oxidized) were identified. Lithoclasts were subdivided into single minerals such as feldspars, olivines, clinopyroxenes, amphiboles, and opaque minerals, as well as rock fragments with various textures: lathwork, microlitic, and vitreous. Intraclasts, in turn, consisted of sedimentary aggregates composed of silt and clay, and other sand grain with carbonate cement.

In addition to the point counts, representative microphotographs (Fig. 7) were taken of the most relevant components from each sample to document their compositional and textural characteristics, contributing to a better interpretation and comparison between the different analysed thin sections.

Table 1. Defined groups for sandy grain identification and letter given to each of them for the PetrogLite software.

LITHOCLASTS	
MINERALS	
P	Feldsparss
O	Olivines
C	Clinopyroxenes
H	Amphipbole
Y	Opaque
ROCK FRAGMENTS	
T	Lathwork texture
M	Microlitic texture
V	Vitric texture
BIOCLASTS	
A	Algae
E	Echinoderms
B	Bryozoans
Z	Calcite mollusks
N	Oxidized mollusks
F	Calcite foraminifera
D	Oxidized foraminifera
INTRACLASTS	
I	Intraclast
L	Silts and clays

4. Results

Microscopic observation revealed a notable compositional variability among the analyzed samples. Based on these observations, five main groups of components were identified: mineral lithoclasts (Lmi), rock fragments (LRf), flora bioclasts (Bfl), fauna bioclasts (Bfa), and intraclasts (INT). These categories were defined according to their morphological, textural, and optical characteristics observed under the microscope, such as grain shape, color, interference color, relief, exfoliation, and fractures, among others.

The data were processed using spreadsheets, where the abundance percentages of each grain type was calculated, along with the mean values and standard deviations for each sedimentary environment (Annexes 1, 2 and 3). These parameters allowed for the estimation of both the typical composition and the degree of heterogeneity of the samples within each of the studied beach-dune systems.

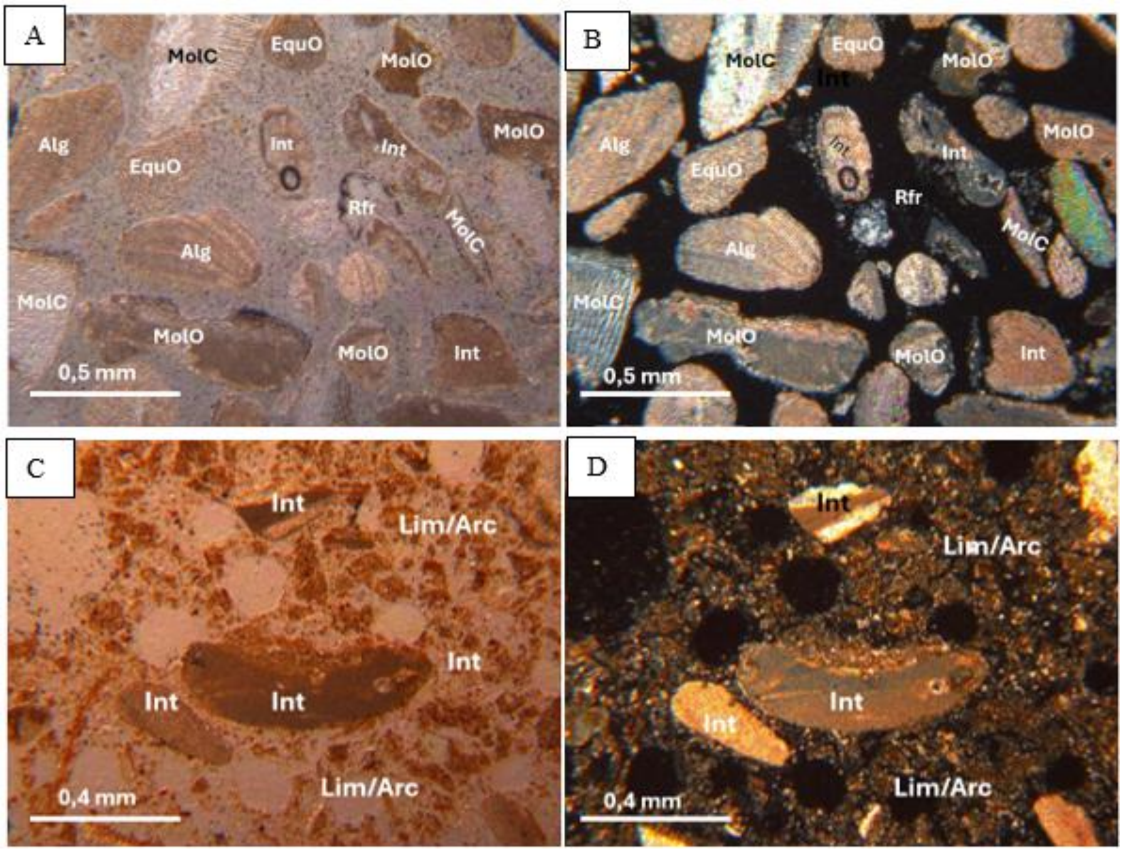

Figure 6. Microphotographs from thin sections under petrographic microscope at 10X magnification. Images **A** and **C** taken under plane-polarized light; images **B** and **D** under cross-polarized light. **A** and **B** show various bioclasts such as algae mesh (Alg), oxidized echinoderms (EquO), calcitic echinoderms (EquC), oxidized mollusks (MolO), calcitic mollusks (MolC), together with intraclasts (Int) and rock fragments (Rfr). Images **C** and **D** correspond to a sample from an endorheic soil, characterized by a high concentration of intraclasts (Int) and fine matrix composed of silt and clay (Lim/Arc).

To facilitate analysis and interpretation, the results were grouped into two main sectors of the island, each containing distinct beach-dune systems: the northern and the central-eastern zones (Figs. 3 and 4). The selected microphotographs (Fig. 6) illustrate some identified grains in the thin sections and clearly hightlight the differences between the various types of clasts.

4.1. North beach–dune systems

The petrographic study of the sediments from the North Systems reveals substantial compositional differentiation among the various sedimentary environments and sampled locations (Fig. 7, Annexes 1 and 2).

In the supratidal zones-fore dune (Fig. 7), sediments are dominated by fauna bioclasts (Bfa), ranging from 47% in Las Conchas to 66.5% in Playa Lambra (Figs. 5C and 10A). Flora bioclasts (Bfl) constitute the second most abundant component (24.5–33.5%). A notably high content of mineral lithoclasts (Lmi) is observed in Playa de Las Conchas (Fig. 5C), significantly higher than that in Playa Lambra (≤1%). Rock fragments (LRf) occur sporadically (≤2.5%), while intraclast (INT) ranges from 6.5% to 16.5% (Annex 1).

These compositional patterns are further supported by the distribution of the samples (Fig. 9A), where data points from Playa Lambra, Jable de La Fragata, and Playa de Las Conchas cluster near the bioclast-rich domain, reinforcing the biogenic dominance in these sites. In contrast, Baja del Ganado displays a more dispersed distribution, reflecting increased lithoclast and intraclast content, indicative of more intense reworking or mixed sedimentary inputs (Fig. 10B).

The nebkhas (Figs. 7 and 10A) exhibit greater compositional heterogeneity. In Playa Lambra, Bfa remains dominant (55.5–61%), followed by Bfl (23.5–29%) and INT (11–13%) (Annex 1). The Jable de La Fragata show marked variability, with values such as 63% Bfa, 15% Bfl, 4% Lmi, and a notable 4.5% LRf. Samples from Las Conchas reveal high internal variability; one shows a more balanced composition (41.6% Bfa, 33.7% Bfl, 13% Lmi), while another is strongly dominated by Bfa (89.5%), with minimal representation of other components. In Baja del Ganado, there is a higher proportion of Lmi (23%) and LRf (7.5%), along with relatively lower Bfa (36.5%) and Bfl (23%) contents (Fig. 10B, Annex 1). These contrasts are reflected in the broader dispersion of nebkhas samples in the compositional diagram (Fig. 9A), particularly for Baja del Ganado.

The sand layers in the Fragata zone are dominated by Bfa (74.5%) and Bfl (15.5%), with moderate LRf (5.5%) and low INT (4.5%) contents (Annex 1).

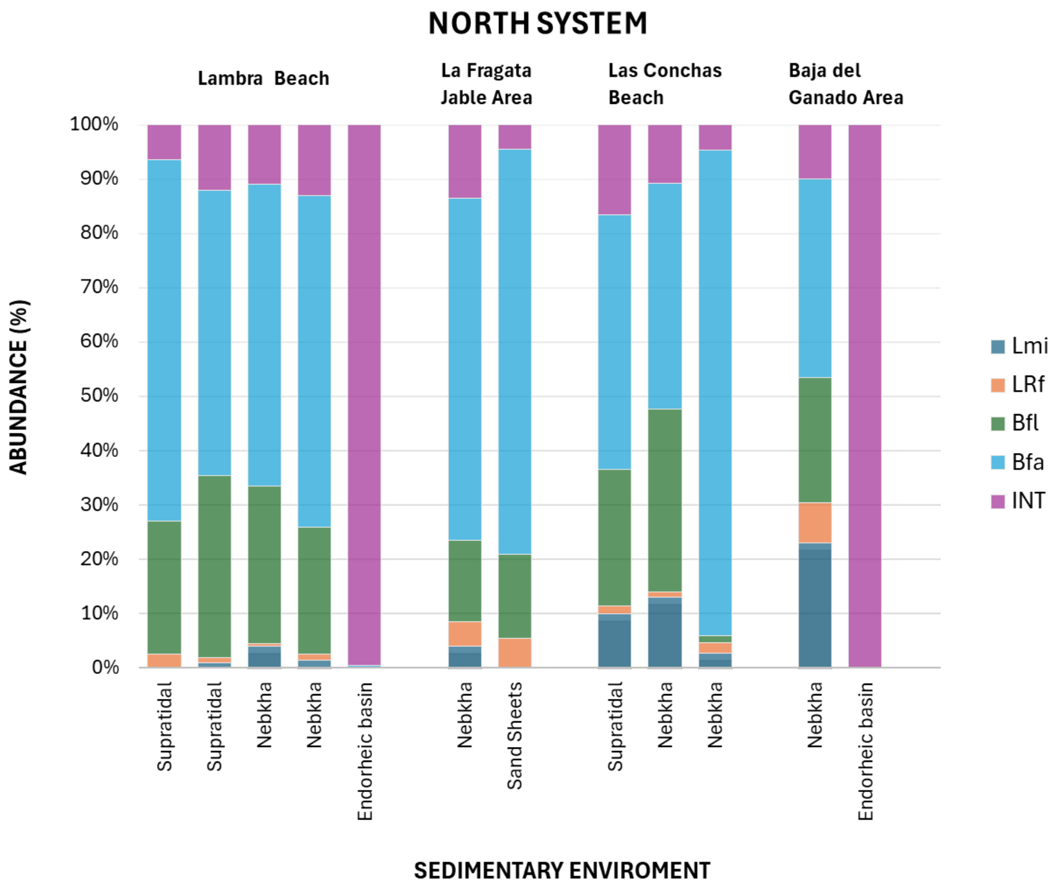

Figure 7. Relative abundance (%) of major grain components (mineral lithoclasts (Lmi), rock fragments (LRf), flora bioclasts (Bfl), fauna bioclasts (Bfa), and intraclasts (INT)) in sediment samples from various depositional environments (supratidal zone, foredune nebkhas, sand sheets, endorheic basin) within the Northern System, including Playa Lambra and Jable de La Fragata in the north zone, and Las Conchas beach and Baja del Ganado in the north western part. Numerical data of relative abundance (%) in annex 2.

In the nebkhas (Fig. 7) of the Fragata zone, Bfa remains the dominant component (74.5%), followed by Bfl (15.5%), with moderate LRf (5.5%) and low INT (4.5%) (Annex 1).

In the endorheic basins (Fig. 7) of Playa Lambra and Baja del Ganado, the aeolian sediments consist predominantly of silt-clay grains and intraclasts (i.e., sand grains with mud matrix), resulting in an INT-dominant composition (99.5–100%), as illustrated by their position near the intraclast vertex in the ternary diagram (Fig. 9).

4.2. Central–Eastern beach–dune systems

The petrographic analysis of sediments from Playa El Salado and the Barranco Conejos–Las Caletas zones reveals compositional variability across the sedimentary environments studied (Figs. 5A, 8 and 10C, D, F).

In the supratidal zones (Fig. 8) of Playa El Salado, sediments are dominated by Bfa (51.6-52%), followed by Bfl (19.5–25.2%) and LRf (6.5–16.1%). One sample exhibits relatively high Lmi content (8%), while another presents very low INT (2.5%) (Annexes 1 and 3).

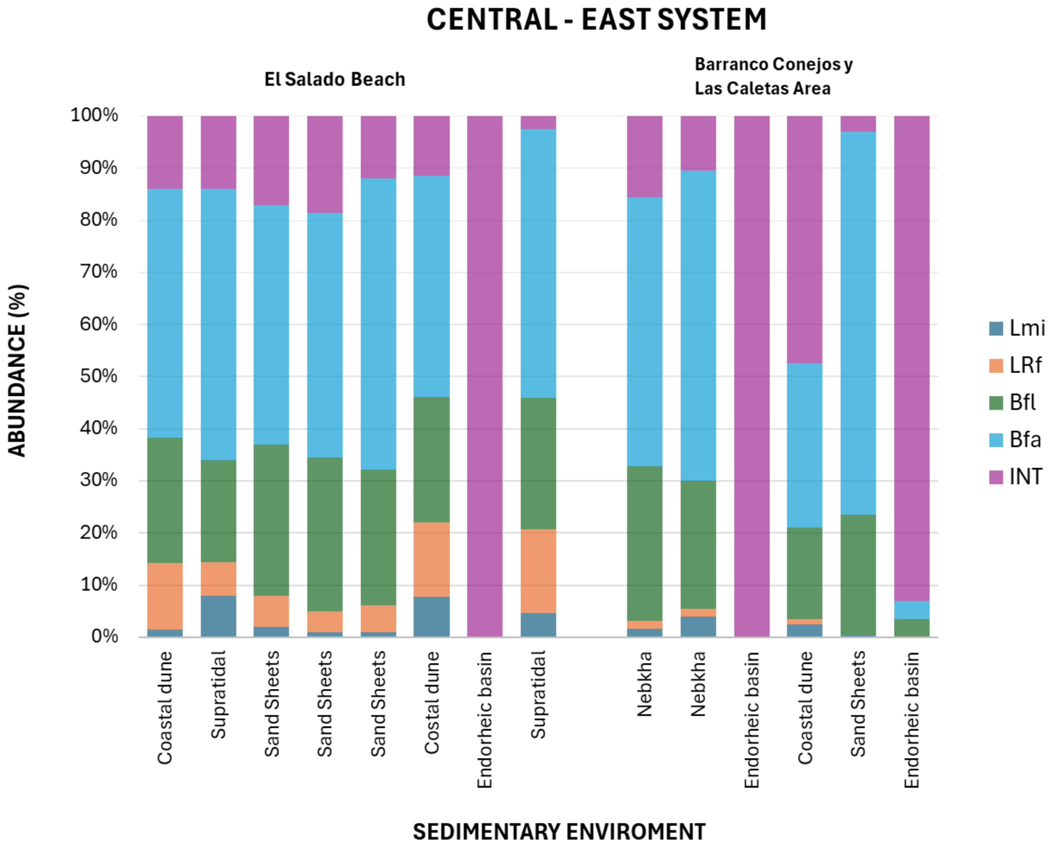

Figure 8. Relative abundance (%) of major grain components (Bfa, Bfl, Lmi, LRf, INT) in sediment samples from different depositional environments (supratidal zone, foredune-coastal dune, sand sheets mantle, endorheic basin) across the El Salado Beach and Barranco Conejos–Las Caletas area, Central–Eastern System. Numerical data of relative abundance (%) in annex 3.

The compositional diversity (Fig. 9B) shows that samples from this environment are concentrated in the bioclast-dominant sector.

In the nebkhas (Fig. 8) of Barranco Conejos–Las Caletas, sediments are also dominated by Bfa (51.7–59.5%), followed by Bfl (24.5–29.6%), with low levels of Lmi and LRf (1.5–4%), and moderate INT (10.5–15.5%). The plotted distributions (Fig. 9B) reflect this trend, with a slight shift toward the intraclast domain, suggesting minor reworking or compositional mixing.

In the sand sheets (Fig. 8) of Playa El Salado, sediments show relatively homogeneous composition, with dominance of Bfa (46–55.9%) and Bfl (26–29.5%), low Lmi (1–2%) and LRf (4–6%), and moderate INT (12–18.5%). Conversely, in Barranco Conejos and Las Caletas, a stronger bioclast dominance is evident (Bfa 73.5%, Bfl 23%) with almost no Lmi or LRf, suggesting a different source area compared to Playa El Salado beach samples (Annex 1). These patterns are consistent across all aeolian samples from the area (Fig. 9B).

In the coastal dune-foredune zone (Fig. 8) of Barranco Conejos–Las Caletas, sediments contain lower Bfa (31.5%) and high INT (47.5%). In contrast, the foredunes of Playa El Salado (GRAC-18 and GRAC-26) exhibit mixed compositions: Bfa (42.4–47.8%), Bfl (24%), notable LRf (12.9–14.3%), and moderate levels of INT (11.5–13.9%) and Lmi (1.4–7.8%) (Annex 1).

Finally, in the endorheic basins (Fig. 8) of Playa El Salado and Barranco Conejos–Las Caletas, sediments consist almost entirely of INT (93–100%), a trend clearly ilustrated in the compositional grouping of these samples (Fig. 9B).

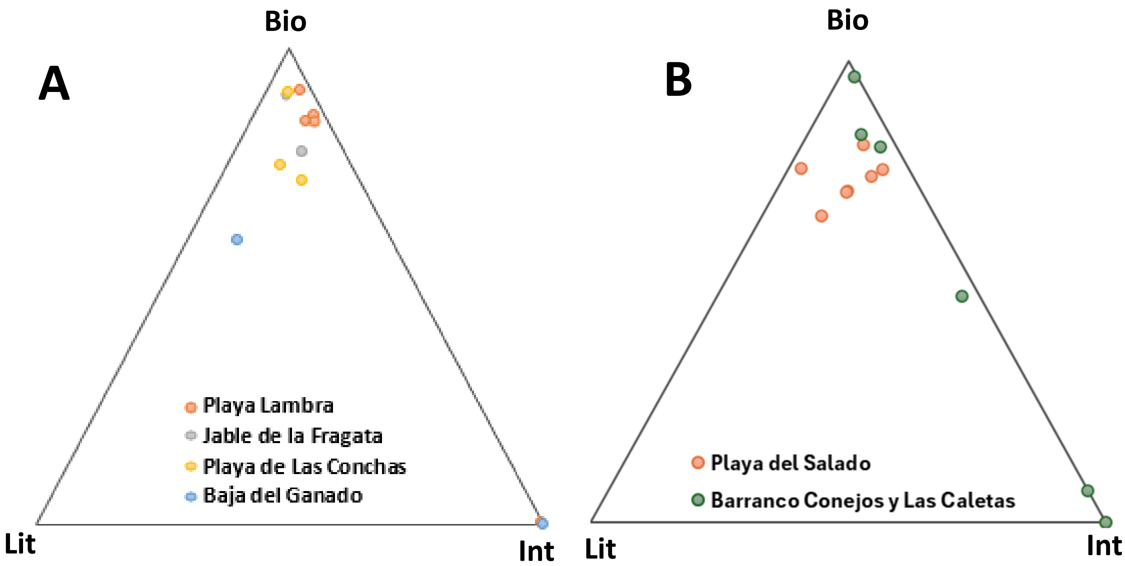

Figure 9. Ternary diagram showing the relative proportions of the main clast types: bioclasts (Bio), intraclasts (Int), and lithoclasts (Lit). Diagram **A)** corresponds to samples from the northern sedimentary system, while diagram **B)** represents those from the central-eastern system. Each point represents an individual sample based on its compositional data.

5. Discussion

First, the results obtained in La Graciosa will be interpreted and discussed, both from the field campaigns and from the petrographic analyses and desktop work; secondly, the data from La Graciosa will be compared with the existing data in the bibliography on beach-dune systems of the eastern Canary Islands.

5.1 Discussion of results obtained on the island of Graciosa

The island of La Graciosa was formed by volcanic processes during the Middle and Upper Pleistocene (less than 800,000 years ago). It has an area of 27.05 km² (Pérez-Chacón et al., 2012), and the beach-dune sedimentary systems occupy almost half of the island, covering an emerged area of 13.1 km² (Fig. 1). These sedimentary systems are composed of loose sandy detrital sediments in subtidal, intertidal, and supratidal zones (Figs. 5B, C and 10). Submerged sandbanks appear discontinuously among volcanic materials and are moved primarily by wave action (with the wave base level at about 25 meters depth) and marine currents.

The subtidal sands are transported by marine dynamics into the more energetic intertidal zones, where waves, tides, and currents are active. In these areas, new detrital sediments enter the system due to the erosion of coastal rocky materials present there (Figs. 5A, B, C, and 10C, D, F). From there, the detrital sediments are transported into supratidal zones, where NE-SW trade winds primarily act and mobilize sand grains to form aeolian deposits (Fig. 10A). During rainfall events, surface water flow and gravity contribute additional sandy grains to the aeolian system (Fig. 10B).

These wind-formed systems, locally known as jables, are distributed across platforms or slopes that extend from the coastline to altitudes of around 50 m on the island (Fig. 10C). Thus, the loose detrital grains that are currently moving (or have been mobilized over the past few hundred years) across these relatively flat and undulating slopes generate various aeolian deposits and sedimentary geoforms: different types of dunes and sand sheets (Fig. 10A). In the endorheic basins, silt-sandy deposits are found, formed by the decantation of fine and medium detrital particles (Fig. 10B; Menéndez et al., 2013).

During the field campaigns for this final degree project, we studied the island's *jables* and analyzed the two main systems that appear: the northern system, which occupies an area of 4.4 km², and the southern system, which occupies 8.7 km² (Pérez-Chacón et al., 2012). These two sedimentary systems are separated by a chain of Pleistocene volcanic eruptions, including Morros Negros, Agujas Grande and Chica, El Mojón (Fig. 10C), and Montaña Amarilla. These eruptions are of ultramafic and mafic composition (basanitic and basaltic) and are characterized by both calm effusive and explosive hydromagmatic activity. This activity gave rise to the formation of various volcanic cones, the emission of lava flows, and the deposition of pyroclastic fall materials (Figs. 1, 3, and 4).

In addition, we observed that the northern *jable* is further subdivided by the effusive Holocene eruption of Montaña Bermeja (cone, lava flows, and basaltic pyroclasts, Fig. 5C), creating two distinct aeolian zones: the subsystem of Playa de Las Conchas and Baja del Ganado in the western part of the island (Figs. 5C and 10B), and three areas in the northern and northeastern parts of the island Playa Lambra to the north (Figs. 5B and 10A), and La Fragata and Pedro Barba to the northeast.

The Pedro Barba *jable* has an area of 0.085 km² (Pérez-Chacón et al., 2012). It is surrounded by volcanic outcrops from the Las Agujas volcanic complex, bordered to the east by the sea. The village and its pier are located on the coast, but currently, this area does not contain loose aeolian sands. For this reason, the Pedro Barba *jable* has not been considered in this study, and no samples were taken for the petrographic analysis.

Figure 10. Various geological and geomorphological aspects of the beach-dune systems of La Graciosa. **A)** Active nebkhas and aeolian sand sheets in the Lambra system; **B)** Aeolian sands stabilized by vegetation and affected by gullies transporting volcanic pyroclasts in the supratidal zone of Baja del Ganado; **C)** Cream-colored jable of Las Caletas bordered by the volcanic alignment of Las Agujas and Morros Negros, which appears in brown tones; **D)** Intertidal and supratidal zone at Caleta de Abajo with no sand input and a semi-active jable; **E)** Urban development and harbor at Caleta de Sebo, which has influenced the sedimentary dynamics of the jable in the eastern part of the island and **F)** Cliffs composed of aeolianites and paleosols, along with a rocky substrate of paleobeach deposits and volcanic flows, which prevent marine sand from entering Salado Beach.

Regarding the beach-dune system in the central-eastern part of the island, it could be considered as a single continuous *jable* stretching from Barranco de Los Conejos in the north (Fig. 10C) to Montaña Amarilla in the south (Fig. 5D). However, we divided it into two subsystems due to the presence of the town of Caleta del Sebo (Fig. 10E), which has expanded in recent decades through construction, road infrastructure, and port development, all of which interfere with the wind dynamics of the system

(Hernández-Calvento et al., 2013; García-Romero et al., 2016; Santana-Cordero et al., 2016; Mangas et al., 2017).

Therefore, we considered two subsystems: the Salado Beach subsystem to the south of the town (Figs. 5A and 10F), and the subsystem of the Conejos and Caletas ravine to the north (Fig. 10D). On the other hand, there are *jable* deposits in the southern and southwestern parts of the island, but they were not studied due to the lack of sandy material and corresponding thin sections for petrographic analysis.

Nevertheless, we consider that the research carried out in this thesis with 21 samples from various aeolian deposits within the beach-dune systems, plus 5 samples from endorheic basins is sufficient to characterize the nature of the aeolian sands and their relative abundance in almost all the beach-dune systems of La Graciosa.

Likewise, during the field campaigns, we confirmed that the only two active beach-dune systems currently receiving sand input from the subtidal to the intertidal and supratidal zones are Las Conchas, along approximately 500 m of coastline, and Lambra, although in the latter only three discontinuous intertidal corridors exist, totaling around 100 m in length (Figs. 5 B and C). The Baja del Ganado subsystem in the north and the Barranco de Los Conejos subsystem in the east are considered semi-active, as sand is present on the beaches, but the existence of meter-high cliff formations prevents marine sediments from reaching the supratidal zones of the beach-dune system.

In the subsystems of Baja del Ganado, La Fragata in the north, and Las Caletas and El Salado in the east and south of the island (Figs. 5 A and 10 D, G), sand transport occurs only by wind action in the supratidal zones of the beach-dune systems. Therefore, these are also considered semi-active, as they currently lack a marine sand supply, instead persisting with ancient sand reserves that have been mobilized and reworked over hundreds or thousands of years. These semi-active beach-dune systems are likely to eventually become inactive, as has already occurred with the Pedro Barba system, which currently has no sediment input into the intertidal zone or aeolian movement of loose sands in the supratidal area.

In light of these field observations, it is unsurprising that recent studies have reported a sand deficit in several beach-dune systems on La Graciosa, such as Baja del Ganado, Lambra, Fragata, Pedro Barba, Las Caletas, Caleta del Sebo, El Salado, and La Francesa (Figs. 5 A, B and 10 C, D) over the last decades (Pérez-Chacón et al., 2010 and 2012; Hernández-Calvento et al., 2013; García-Romero et al., 2016; Santana-Cordero et al., 2016, Mangas et al., 2017).

From the petrographic interpretation of the data obtained in this study (Annexes 1, 2 and 3, Figs. 7, 8, and 9), we first highlight that grains of bioclastic (organogenic) origin have an average abundance of 77.5% (σ=8.6), making them the most common in the aeolian sands studied. Terrigenous grains (including sedimentary intraclasts, rock fragments, and mafic volcanic minerals) are less abundant, with an average of 22.5%. Among the bioclasts, fauna-derived grains dominate, averaging 55.9% primarily consisting of mollusc remains, and less frequently fragments of echinoderms, foraminifera, and bryozoans. These are followed by marine flora bioclasts, primarily fragments of coralline red algae (rhodoliths, commonly known as " popcorn"), which average 22.6%. In second place, sedimentary carbonate intraclasts have an average abundance of 14.5% ($\sigma = 5.9$), and volcanic lithoclasts (rock and mafic volcanic mineral fragments) average 8% ($\sigma = 1$).

When comparing these data with those from a petrographic study of 40 submerged sand samples collected near the island's beach-dune systems (Mangas et al., 2017), similar bioclast percentages were observed 88% in the northern systems and 76% in the eastern and southern systems, with an island-wide average of 82%. Faunal bioclasts predominate over floral ones, as also observed in the aeolian sands.That study also reported intraclast values of 5%, which is half of what we observed in this final degree project. For volcanic lithoclasts, submerged sands in the northern sector showed 9%, similar to our results. However, in the eastern and southern sectors, submerged sands had values of 17.5% more than double the amount recorded in our aeolian samples. This suggests more intense submarine and subaerial erosional processes in these areas, generating a greater abundance of such grains.

It can thus be inferred that the submerged sands the primary source of aeolian bioclastic grains show a reduction in intraclast content. These intraclasts likely originated from the subaerial erosion of paleosol, paleodune, and paleobeach layers found along the island's coast. Regarding volcanic lithoclasts, the significantly higher values in the submerged sands of the east and south suggest major subaerial and submarine erosion of volcanic substrates in these areas.

This general trend in the relative average abundances on La Graciosa is broadly consistent across the northern and central-eastern systems, though slight differences can be seen among specific supratidal aeolian deposits (e.g., foredunes, nebkhas, and aeolian sheets). For instance, in the northern subsystems, bioclasts average 77.3%, with faunal bioclasts at 55.9% ($\sigma = 11$) and floral at 21.5% ($\sigma = 8.5$). In the central-eastern sector, bioclasts average 77.7%, with 54.1% ($\sigma = 9.2$) faunal and 23.7% ($\sigma = 1.1$) floral.

These results suggest that the source of bioclastic grains in aeolian deposits is consistent and derived from similar subtidal sandbanks around La Graciosa. However, differences emerge in terrigenous content: sedimentary intraclasts average 9.8% ($\sigma = 1.9$) in the north and 15.9% ($\sigma = 10.3$) in the central-east, suggesting greater erosion of substrates containing paleosols and paleodunes in areas such as Las Caletas.

Volcanic lithoclasts average 13% ($\sigma = 1.9$) in the north and 8.2% ($\sigma = 3.4$) in the central-east, indicating more erosion of volcanic substrates (cones, lavas, and pyroclasts from the N45E volcanic alignment and Montaña Bermeja (Fig. 1) in the north. In this regard, the Baja del Ganado subsystem stands out with a high average of volcanic lithoclasts (30.5%), accompanied by a reduced bioclast percentage (59.5%). This is due to ravines transporting basaltic pyroclasts into the supratidal aeolian zone during rainy periods.

A similar process occurs at Las Conchas, where volcanic lithoclasts reach 10%, linked to erosion of nearby Montaña Bermeja and subsequent sediment transport to the beach-dune system. In El Salado system of the central-east, volcanic lithoclasts average 13%, attributed to erosion of volcanic rocks from El Mojón and associated ravine transport.

In contrast, the beach at Lambra (north) has very low volcanic lithoclast values (2.9%), as does the Barranco de Los Conejos–Caletas system (central-east, 3.4%), likely due to the absence of nearby volcanic rock sources, both submerged and exposed, and no significant terrigenous transport into these aeolian systems.

Finally, the sand and silt-clay samples from endorheic basins showed homogeneous petrographic results, composed predominantly of sedimentary intraclasts (98.5%), with a minor bioclastic component (1.5%).

5.2 Comparison of La Graciosa data with the beach-dune systems of Lanzarote, Fuerteventura, and Gran Canaria

Elsewhere in the eastern Canary Islands, major beach-dune systems include the aeolian corridor from Caleta de Famara to Arrecife in Lanzarote, the Dunes of Corralejo Natural Park in Fuerteventura, and the Maspalomas Dunes Special Nature Reserve in Gran Canaria (Fig. 11). These systems remain active but are affected by sand loss due to urban and tourism development since the 1970s.

These older islands, geologically speaking, have well-developed subtidal zones and insular platforms (less than 200 m in depth) that host sandbanks. These act as sand reserves supplying aeolian systems via marine dynamics (waves, currents, tides) under both modern and past conditions. During glacial periods, sea levels fell by up to 150 m, exposing these sandbanks and enabling their remobilization to form aeolian deposits at the surface, which eventually cemented into aeolianites.

In Lanzarote, the NW-SE aeolian corridor extends several kilometers, encompassing foredunes, nebkhas, barchan dunes, and extensive aeolian sheets, originating at Famara Beach in the northwest and terminating near the beaches of Arrecife (Figs. 11A and B). It is bounded to the north by the Famara cliffs, composed of Miocene-Pliocene volcanic materials and Quaternary colluvial and alluvial deposits (Fig. 11A), and to the south by monogenetic Quaternary volcanic eruptions and sedimentary aeolianites with meter-scale thicknesses (Fig. 11B).

Aeolian sands enter primarily through La Caleta and Famara Beach (Fig. 11A), traverse the corridor where they mix with new detrital grains (both volcanic and sedimentary), and exit toward the capital area, where human activities have introduced further sedimentary inputs.

Figure 11. Different geological, geomorphological, and anthropogenic aspects of the beach-dune systems of Famara-Arrecife (Lanzarote), Corralejo (Fuerteventura), and Maspalomas (Gran Canaria). **A)** Nebkhas and eolian sheets in the intertidal and supratidal zones at Caleta de Famara; **B)** Barchan dune in 2009, now disappeared, and aeolian sheets stabilized by vegetation with reduced mobility; **C)** Urban developments north of the Corralejo Natural Park affecting wind flow and marine sand input; **D)** Southern area of the Corralejo Natural Park where barchan dunes and active aeolian sheets can still be observed, although the amount of sand has decreased since the 1970s; **E)** General view of the Maspalomas dune field with various aeolian deposits (foredunes, nebkhas, barchan dunes, and eolian sheets), although sand loss has also been detected since tourism development; **F)** Input of the volcanic lithoclast and sedimentary intraclast grains when the Fataga ravine overflows the Maspalomas lagoon after heavy rains.

A sedimentological study by Cabrera-Vega (2013) of this aeolian system analyzed various types of sediment, finding that in a dozen aeolian sand samples from dunes and aeolian mantles, bioclasts averaged 48% (35.6% fauna, 12.4% flora). Volcanic silicate terrigenous grains (from basanitic and basaltic rocks of the Famara and Quaternary volcanoes) averaged 40.9%, and sedimentary intraclasts (from aeolianite, paleosols, and paleobeach substrates southwest of Caleta de Famara) made up 11.1%.

Therefore, the aeolian sands of the Famara *jable* are richer in volcanic lithoclasts than those of La Graciosa, due to surface runoff erosion of nearby volcanic materials transported downslope through ravines into the lower parts of the aeolian corridor.

In the natural park of the dunes of Corralejo, NE of Fuerteventura (Figs. 11C and D), García-Sanjosé (2013), in his Master's thesis in Coastal Management, studies the geological characteristics of the volcanic and sedimentary materials that emerge on the coast of this protected area, in order to highlight this particular geodiversity. In this study, García-Sanjosé analyzes the composition of some samples of intertidal sands and coastal dunes, indicating that the sands are fundamentally bioclastic, with relative abundance percentages of fauna and flora of around 90%, followed by sedimentary intraclasts with values of 7%, while volcanic lithoclasts have only average values of 3%. Sedimentary materials predominate in the protected area, although there are volcanic materials from the Middle and Upper Pleistocene around the natural park and in some coastal outcrops (Fig. 11C). The topography of the natural park is almost flat, with hilly plains and no ravines (Fig. 11D), and small cliffs appear along the coast. The climate is coastal desert, so rainfall is very low, on the order of less than 100 mm per year. For all these reasons, the organogenic aeolian sands (mostly remains of fauna and, to a lesser extent, flora) that predominate come directly from the subtidal banks, reach the intertidal zone characterized by various sandy coves and the presence of scarce sedimentary and volcanic rocky substrates and are then transported by the wind into the interior of the protected area. Therefore, the wind-blown sands of Corralejo are more bioclastic in nature than those of La Graciosa, and the grains of sedimentary and volcanic terrigenous materials are in the minority. In recent decades, urban tourist development has cut off the marine contributions of sand to the Corralejo system in the NE (Fig. 11C), and, in addition, sand was extracted as construction aggregate during the urbanization of this area (although since 1987, when it was declared a protected area, mining extraction has been prohibited), resulting in a notable deficit of wind-blown sand on the beaches and in the dune field, with outcrops of rocky substrates now visible throughout this space.

In Gran Canaria, the active beach-dune system is the protected area of the Maspalomas Dunes Special Nature Reserve (Figs. 11E and F), although it shows significant environmental problems due to tourist development in recent decades. Hernández-Calvento and Mangas (2004) conducted a petrographic study of the sedimentary materials (rocks and loose sands) of this protected area. Regarding the aeolian sands, these authors indicate average values of bioclastic grain abundance of 49%, of which 34.8% are remains of coralline red algae meshes, 11.8% are fragments of molluscs, and 3% are from other organisms such as bryozoans, foraminifera, and echinoderms. The abundance of volcanic lithoclasts reaches average values of 39%, with 20% being mafic grains (fragments of basalt and basanite rocks, and minerals such as olivine, clinopyroxene, amphibole, and iron oxides), and 19% felsic detritals (pieces of trachytes and phonolites, and especially minerals such as feldspars and feldspathoids). Sedimentary intraclasts are the least abundant grains, with average percentages of 12%. The presence of the mouth of the Fataga-Maspalomas ravine in the area of the Charca de Maspalomas, and its activity during the rainy season, occasionally transports volcanic lithoclasts from the interior of the island and the surroundings of the Special Reserve to the dune system. In addition, Pleistocene paleobeach substrates and alluvial sedimentary deposits emerge at the mouth of the ravine and in the surrounding area, so their erosion by fluvial and marine dynamics contributes sedimentary intraclasts, although these are a minority in the aeolian system. Therefore, the sands of Maspalomas are richer in flora-derived grains and volcanic lithoclasts than those of La Graciosa, and, additionally, felsic volcanic rock terrigens appear here, which do not exist on the island.

In the literature, no petrographic studies of aeolian sands have been found in beach-dune systems of oceanic volcanic islands associated with hot spots, such as the Canary Archipelago. However, there are analyses of beach sands in the Hawaiian Islands and Cape Verde (Marsaglia, 1993; Le Pera et al., 2021). Nevertheless, we are not going to consider them, since they did not study the supratidal sands in the wind systems associated with these beaches.

On the other hand, although it is not the objective of this thesis, the bibliography on aeolianite deposits in coastal areas of the eastern Canary Islands which have ages ranging from the Pliocene to the Quaternary has been analyzed, indicating that beach-dune systems have existed in the archipelago for about 5 million years (Meco et al., 2006; Mangas et al., 2008a and b; Sánchez-Pérez et al., 2008, etc.). These ancient aeolian processes have also been identified in several coastal locations at various latitudes (Brooke, 2001; Johnson et al., 2013, among others). In almost all of them, petrographic studies show that aeolianites are predominantly composed of grains of marine fauna and flora bioclasts, although in some cases terrigens (silicate and intraclast lithoclasts) are also prominent. Furthermore, the cements that bind the grains in the aeolianites are carbonates, specifically calcium carbonates (magnesian calcite crystals) and aragonite.

6. Conclusions

The petrographic data obtained from the study of 21 samples of aeolian sands and 5 detrital sediments from endorheic basins across 6 beach-dune systems on the island of La Graciosa reveal the nature of the sand grains, their relative abundance, and the variability of their different source areas. The main conclusions are as follows:

1. In the studied beach-dune systems, there are sedimentary deposits and geoforms where sands are moved by the dominant wind (northeast–southwest trade winds), distributed from intertidal zones to supratidal areas, forming coastal foredunes, nebkhas, and aeolian sheets, and to a lesser extent, transported toward endorheic basins. In these endorheic basins, in addition to wind-blown sands, fine and very fine sediment grains (silts and clays) appear, which have been transported by both wind and surface waters, and all are deposited by settling on the basin floor when they dry up.
2. The aeolian sands from the six beach-dune systems in the northern and central-eastern parts of the island are predominantly composed of marine bioclast fragments (average of 77.5%). Mollusk remains are the most abundant, averaging 55%, followed by coralline red algae at 22.5%. Other marine bioclasts, such as foraminifera, echinoderms, and bryozoans, occur in very low or negligible quantities. These results indicate that most of the aeolian sands forming the island's *jables* are primarily of marine origin.
3. The aeolian sands contain low proportions of lithoclasts, both from volcanic rock fragments, minerals, and glasses, with average values of 8% ($\sigma = 1$). There are various outcrops of volcanic materials from the Pleistocene (cones, lava flows, and pyroclastic fall deposits), both on the coast and inland on the island. However, current and recent geological erosive agents (sea, surface water, gravity, and wind) are not sufficient to generate terrigenous grains and act as significant sources of sand. The composition of these identified lithoclasts includes volcanic rocks of ultramafic and mafic composition (basanites with olivine, opaque minerals, and volcanic glass; and basalts with olivine, clinopyroxenes, feldspars, opaque minerals, and volcanic glass, respectively).
4. The sand grains of bioclastic and lithoclastic nature sometimes agglomerate with carbonate cements of marine origin and/or fine grains of silts and clays, forming intraclasts, which show average values of 14.5% ($\sigma = 5.9$). These intraclasts mainly originate from the erosion of Pleistocene and Holocene sedimentary rocks such as paleosols, paleodunes, and paleobeaches, which are common substrates in the analyzed beach-dune systems. These sedimentary rocks are softer than volcanic ones, making them more susceptible to erosion. The relative abundance percentages of intraclasts in the studied samples are moderate to low in the aeolian deposits, but they are predominant or even exclusive in the endorheic basins (average data: 98.5% intraclasts, and 1.5% grains from fauna and flora).

5. The general analysis of the aeolian samples shows similar trends, with a predominance of bioclasts (remains of marine fauna and flora) over terrigenous materials (volcanic lithoclasts and sedimentary intraclasts). However, small variations are observed in their relative abundance values among the different studied aeolian systems on the island. These variations are due to geological conditions (presence or absence of outcrops of volcanic or sedimentary substrates in or near the system), geographical factors (existence of rocky coasts or cliffs, ravines or gorges, plains or slopes, etc.), and anthropogenic factors (port constructions, residential areas, and road infrastructures), all of which influence slight differences in the abundance percentages across the different systems. These natural and anthropogenic factors also contribute to the small variability in the data observed in aeolian deposits (supratidal zones, foredunes, nebkhas, aeolian sheets), while the data from the endorheic basins are more homogeneous.
6. The petrographic data on the relative abundance of the main types of sand grains in La Graciosa have been compared with studies conducted on significant beach-dune systems of the eastern Canary Islands (Famara-Arrecife in Lanzarote, Corralejo in Fuerteventura, and Maspalomas in Gran Canaria). Thus, it is evident that no two aeolian deposits are identical, and they present different values of bioclasts, volcanic lithoclasts, and sedimentary intraclasts, due to local characteristics such as different geological materials, geoforms, and anthropogenic impacts both within the sedimentary systems themselves and in their surroundings. Moreover, cemented aeolian deposits (*aeolianites*) appear at various latitudes on Earth, from equatorial to polar regions. They exist in the Canary Islands, in other archipelagos, and in coastal continental areas. In these aeolianites, grains of bioclastic composition also predominate, as is the case in the data obtained for La Graciosa. However, the nature of the abundant bioclasts can vary, including coral fragments, algal meshes, foraminifera, and other marine organisms.

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Annex 1: Petrographic data

Beach	Enviroment	Sample	Lmi Total (%)	LRf Total (%)	Bfl Total (%)	Bfa Total (%)	INT Total (%)
Playa Lambra	Supratidal	GRAC-2A	0	2,5	24,5	66,5	6,5
	Supratidal	GRAC-2B	1	1	33,5	52,5	12
	Nebkha	GRAC-3A	4	0,5	29	55,5	11
	Nebkha	GRAC-4A	1,5	1	23,5	61	13
	Endorheic basin	GRAC-5A	0	0	0	0,5	99,5
Zona Jable de La Fragata	Nebkha	GRAC-12	4	4,5	15	63	13,5
	Sand Sheets	GRAC-13	0	5,5	15,5	74,5	4,5
Playa Las Conchas	Supratidal	GRAC-57	10	1,5	25	47	16,5
	Nebkha	GRAC-59	13	1	33,7	41,6	10,7
	Nebkha	GRAC-61	2,8	1,8	1,3	89,5	4,6
Zona de Baja del Ganado	Nebkha	GRAC-62	23	7,5	23	36,5	10
	Endorheic basin	GRAC-65	0	0	0	0	100
Playa El Salado	Coastal dune	GRAC-18	1,4	12,9	24	47,8	13,9
	Supratidal	GRAC-19	8	6,5	19,5	52	14
	Sand Sheets	GRAC-20	2	6	29	46	17
	Sand Sheets	GRAC-22	1	4	29,5	47	18,5
	Sand Sheets	GRAC-23	1	5,1	26	55,9	12
	Costal dune	GRAC-26	7,8	14,3	24	42,4	11,5
	Endorheic basin	GRAC-27D	0	0	0	0	100
	Supratidal	GRAC-29	4,6	16,1	25,2	51,6	2,5
Zona de Barranco Conejos y Las Caletas	Nebkha	GRAC-34	1,7	1,5	29,6	51,7	15,5
	Nebkha	GRAC-35	4	1,5	24,5	59,5	10,5
	Endorheic basin	GRAC-36	0	0	0	0	100
	Coastal dune	GRAC-40	2,5	1	17,5	31,5	47,5
	Sand Sheets	GRAC-42	0,5	0	23	73,5	3
	Endorheic basin	GRAC-47	0	0	3,5	3,5	93

Annex 1. Petrographic data. Total percentage of each component, resulting from point counting performed on thin sections. The following abbreviations are used: LMi= lithoclast minerals; LRf= lithoclast rock fragments; Bfl= bioclasts flora; Bfa= bioclasts fauna and INT= intraclasts.

Annex 2: Petrographic Data from the Northern Beach–Dune System

		Lithoclast										Bioclast								Intraclast (INT)		
		Minerals (Lmi)						Rock fragments (LRf)				Bioclast flora (Bfl)	Bioclast fauna (Bfa)									
Beach	Sample	P	O	C	H	Y	Total (%)	T	M	V	Total (%)	A	E	B	Z	N	F	D	Total (%)	I	L	Total (%)
Playa Lambra	GRAC-2A	0	0	0	0	0	0	0,5	2	0	2,5	24,5	5,5	0	44	14	1	2	91	6,5	0	6,5
	GRAC-2B	0,5	0	0,5	0	0	1	0,5	0	0,5	1	33,5	1	0	39,5	12	0	0	86	12	0	12
	GRAC-3A	0	4	0	0	0	4	0	0,5	0	0,5	29	4,5	1	37	12	1	0	84,5	11	0	11
	GRAC-4A	0	1,5	0	0	0	1,5	1	0	0	1	23,5	2,5	0	50,5	7,5	0	0,5	84,5	13	0	13
	GRAC-5A	0	0	0	0	0	0	0	0	0	0	0	0	0	0,5	0	0	0	0,5	39,5	60	99,5
	MEAN	0,1	1,1	0,1	0	0	1,3	0,4	0,5	0,1	1	22,1	2,7	0,2	34,3	9,1	0,4	0,5	69,3	16,4	12	28,4
	DESV TIPICA	0,2	1,56	0,20	0,00	0,00	1,47	0,37	0,77	0,20	0,84	11,61	2,06	0,40	17,51	5,02	0,49	0,77	34,48	11,76	24,00	35,62
Zona Jable de La Fragata	GRAC-12	0	3,5	0,5	0	0	4	0	2,5	2	4,5	15	4,5	0,5	39	13,5	1,5	4	78	13,5	0	13,5
	GRAC-13	0	0	0	0	0	0	1,5	4	0	5,5	15,5	9	0,5	51	9	5	0	90	4,5	0	4,5
	MEAN	0	1,75	0,25	0	0	2	0,75	3,25	1	5	15,25	6,75	0,5	45	11,25	3,25	2	84	9	0	9
	DESV TIPICA	0	1,75	0,25	0	0	2	0,75	0,75	1	0,5	0,25	2,25	0	6	2,25	1,75	2	6	4,5	0	4,5
Playa Las Conchas	GRAC-57	1,5	8,5	0	0	0	10	0,5	1	0	1,5	25	3,5	0	27,5	16	0	0	72	16	0,5	16,5
	GRAC-59	0	13	0	0	0	13	0	1	0	1	33,7	1	0	21,8	18,8	0	0	75,3	10,7	0	10,7
	GRAC-61	0,5	2,3	0	0	0	2,8	0	0,9	0,9	1,8	1,3	0	0,5	10,5	78,5	0	0	90,8	4,6	0	4,6
	MEAN	0,67	7,93	0,00	0,00	0,00	8,60	0,17	0,97	0,30	1,43	20,00	1,50	0,17	19,93	37,77	0,00	0,00	79,37	10,43	0,17	10,60
	DESV TIPICA	0,62	4,39	0,00	0,00	0,00	4,28	0,24	0,05	0,42	0,33	13,69	1,47	0,24	7,06	28,83	0,00	0,00	8,20	4,66	0,24	4,86
Zona de Baja del Ganado	GRAC-62	5	18	0	0	0	23	1	6,5	0	7,5	23	0,5	0	30	6	0	0	59,5	10	0	10
	GRAC-65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	52	48	100
	MEAN	2,5	9	0	0	0	11,5	0,5	3,25	0	3,75	11,5	0,25	0	15	3	0	0	29,75	31	24	55
	DESV TIPICA	2,5	9	0	0	0	11,5	0,5	3,25	0	3,75	11,5	0,25	0	15	3	0	0	29,75	21	24	45

Annex 2. Description of the abbreviations used in petrographic analysis. Total percentage of each component, resulting from point counting performed on thin sections. P= feldspars; O= olivines; C= clinopyroxenes; H= amphiboles; Y= opaque minerals; T= lathwork texture; M= microlitic texture; V= vitric texture; A= algae; E= echinoderms; B= bryozoans; Z= calcite mollusks; N= oxidized mollusks; F= calcite foraminifera; D= oxidized foraminifera; I= intraclasts; L= silts and clays. These same abbreviations apply also to **Annex 3.**

Annex 3: Petrographic Data from the Central-East Beach–Dune System

		Lithoclast										Bioclast								Intraclast (INT)		
		Minerals (Lmi)						Rock fragments (LRf)				Bioclast flora (Bfl)	Bioclast fauna (Bfa)									
Beach	Sample	P	O	C	H	Y	Total (%)	T	M	V	Total (%)	A	E	B	Z	N	F	D	Total (%)	I	L	Total (%)
Zona de Playa El Salado	GRAC-18	0	1,4	0	0	0	1,4	1,9	7,2	3,8	12,9	24	1,4	0	33	10	2,4	1	71,8	13,9	0	13,9
	GRAC-19	3	5	0	0	0	8	0	5,5	1	6,5	19,5	0,5	0,5	37,5	12	0,5	1	71,5	12,5	1,5	14
	GRAC-20	0	2	0	0	0	2	0	5,5	0,5	6	29	2	0	29	12	1	2	75	17	0	17
	GRAC-22	0	1	0	0	0	1	3	1	0	4	29,5	3,5	0,5	35,5	5,5	2	0	76,5	18,5	0	18,5
	GRAC-23	0	1	0	0	0	1	0,6	4,5	0	5,1	26	5	0	37	9,9	0	4	81,9	12	0	12
	GRAC-26	0,5	7,3	0	0	0	7,8	0,5	11,3	2,5	14,3	24	0	0	29,4	11	0	2	66,4	11,5	0	11,5
	GRAC-27D	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	33,5	66,5	100
	GRAC-29	0,5	3,6	0,5	0	0	4,6	0	14,6	1,5	16,1	25,2	3,4	0	33	10,3	0,5	4,4	76,8	2,5	0	2,5
	MEAN	0,5	2,66	0,06	0,00	0,00	3,23	0,75	6,20	1,16	8,11	22,15	1,98	0,13	29,30	8,84	0,80	1,80	64,99	15,18	8,50	23,68
	DESV TIPICA	0,97	2,30	0,17	0,00	0,00	2,97	1,04	4,57	1,29	5,29	8,87	1,73	0,22	11,46	3,85	0,88	1,56	24,93	8,24	21,93	29,20
Zona de Barranco Conejos	GRAC-34	0,7	1	0	0	0	1,7	0	1,5	0	1,5	29,6	3,4	0	31,5	14,3	0,5	2	81,3	15,5	0	15,5
	GRAC-35	2	1,5	0,5	0	0	4	0	1	0,5	1,5	24,5	3	1	33,5	14,5	1	6,5	84	10,5	0	10,5
	GRAC-35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	61,2	38,8	100
	GRAC-40	1,5	1	0	0	0	2,5	0	1	0	1	17,5	2	0	19	6	1	3,5	49	47,5	0	47,5
	GRAC-42	0	0,5	0	0	0	0,5	0	0	0	0	23	10,5	1	49,5	3	5	4,5	96,5	3	0	3
	GRAC-47	0	0	0	0	0	0	0	0	0	0	3,5	0	0	1	0	0,5	2	7	58,5	34,5	93
	MEAN	0,70	0,67	0,08	0,00	0,00	1,45	0,00	0,58	0,08	0,67	16,35	3,15	0,33	22,42	6,30	1,33	3,08	52,97	32,70	12,22	44,92
	DESV TIPICA	0,80	0,55	0,19	0,00	0,00	1,46	0,00	0,61	0,19	0,69	10,95	3,54	0,47	17,85	6,08	1,67	2,07	37,85	23,69	17,32	39,07

Valoración personal del trabajo de fin de grado

1. **Descripción detallada de las actividades desarrolladas durante la realización del TFT**

   En primer lugar, se llevó a cabo una revisión bibliográfica sobre los distintos sistemas playa-duna a nivel mundial, con el fin de obtener una visión más amplia del tema. Asimismo, se recopiló información sobre la petrográfica de sedimentos arenosos y los métodos analíticos disponibles, lo que permitió fundamentar teóricamente el estudio. Por otro lado, se seleccionaron los distintos puntos de muestreo en La Graciosa para proceder a la recolección de muestras en playas y ambientes sedimentarios de interés, asegurando la representatividad de las muestras para cada entorno (supramareal, montículo dunar, manto eólico, duna costera y cuenca endorreica). La observación microscópica se realizó utilizando un microscopio petrográfico equipado con un sistema SteppingStage, lo que permitió la identificación y clasificación automatizada de los granos. Los datos obtenidos fueron registrados en hojas de cálculo para su posterior procesamiento estadístico.
   Se calcularon los porcentajes relativos de los diferentes componentes sedimentarios (litoclastos minerales, fragmentos de roca, bioclastos de flora, bioclastos de fauna e intraclastos), y se efectuaron análisis comparativos entre las distintas áreas y entornos. Los resultados se organizaron en tablas y gráficos para facilitar su interpretación.
   Finalmente, se redactaron los informes y capítulos del TFT, integrando la revisión bibliográfica, la metodología, los resultados y la discusión, culminando con las conclusiones y recomendaciones basadas en los hallazgos del estudio.

2. **Formación recibida (cursos, programas informáticos, etc.)**

   Durante la realización del Trabajo de Fin de Grado, recibí formación práctica y teórica en el análisis petrográfico de sedimentos, incluyendo el manejo del microscopio petrográfico equipado con el sistema automatizado SteppingStage y el software PetrogLite para la identificación y clasificación precisa de los granos. Además, adquirí habilidades en el procesamiento y análisis estadístico de datos utilizando Excel, lo que me permitió un tratamiento riguroso de la información. También me familiaricé con diversas técnicas de muestreo y con la interpretación de ambientes sedimentarios costeros, lo que facilitó la integración de los datos petrográficos con los contextos geológicos y ambientales del área estudiada.

3. **Nivel de integración e implicación dentro del departamento y relaciones con el personal.**
   Durante el transcurso del curso, recibí un seguimiento muy cercano y eficaz por parte de ambos tutores. Por un lado, la Dra. Inmaculada Menéndez realizó las correcciones de manera rápida y precisa, lo que facilitó un avance constante y ordenado del proyecto, además de aportar valiosas sugerencias. Por otro lado, el Dr. José Mangas proporcionó su contacto vía WhatsApp, respondiendo siempre con rapidez, amabilidad y disponibilidad, resolviendo cualquier duda con claridad y paciencia. Esta comunicación directa y accesible resultó fundamental para mantener el ritmo del trabajo y asegurar una correcta comprensión del mismo. En conjunto, el apoyo y la orientación de ambos tutores fueron clave para el desarrollo exitoso del proyecto.

4. **Aspectos positivos y negativos más significativos relacionados con el desarrollo del TFT**
   Lo mejor durante el desarrollo del Trabajo de Fin de Grado fue la comunicación rápida y cercana con ambos tutores. Gracias a eso, pude resolver dudas casi al momento y recibir correcciones que me ayudaron a avanzar de forma ordenada y sin problemas.
   En cuanto a lo negativo, realmente no hubo nada destacable que dificultara el trabajo. El apoyo y la coordinación con los tutores hicieron que todo fuera mucho más sencillo y fluido.

5. **Valoración personal del aprendizaje conseguido a lo largo del TFT.**
   En mi valoración personal, el desarrollo del trabajo ha sido una experiencia muy enriquecedora, tanto a nivel académico como personal. He adquirido conocimientos sólidos en análisis petrográfico, manejo de herramientas y técnicas de muestreo, así como en el tratamiento e interpretación de datos.
   Quiero expresar un agradecimiento muy especial al Dr. José Mangas, quien hizo un gran esfuerzo al llevarme personalmente a La Graciosa para que pudiera conocer más en detalle la zona de estudio. Esta visita fue fundamental para comprender mejor el contexto y facilitó enormemente mi trabajo. Además, junto con una compañera, tuvimos la oportunidad de visitar el sistema dunar de Corralejo en Fuerteventura, lo que amplió aún más mi perspectiva sobre los ambientes dunares y complementó perfectamente mi formación.
   Estas experiencias prácticas, unidas al apoyo constante de los tutores, han sido clave para que el aprendizaje fuera completo y significativo.