



Composition and provenance of beach sands in La Graciosa, Lanzarote, Fuerteventura and Gran Canaria Islands (eastern Canary Islands, Spain): a review

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Abstract

In this work, a review of petrographic studies in recent decades on 50 sandy beach samples of the eastern Canary Islands (La Graciosa, Lanzarote, Fuerteventura and Gran Canaria) has been carried out in order to know the composition and provenance of the sand grains. The sandy samples are intertidal and most are related to beach-dune systems with coastal desert and arid climates. Thus, these samples contain different proportions of calcareous bioclast, intraclast and volcanoclast grains, with the latter coming from different source areas associated with the building stages of the islands (shield, decline, erosive and rejuvenation). In general, the calcareous bioclasts are mostly fragments of red coralline algae and molluscs, with the appearance of occasional grains of echinoderms, foraminifera and bryozoans. The lithoclasts are essentially fragments of ultramafic and mafic alkaline rocks (basanite and basalt) from the shield and rejuvenation stages and to a lesser extent trachytic-phonolitic felsic rocks from the decline stage, while there are few mafic (olivine, clinopyroxene, Fe-Ti oxide, and amphibole) and felsic (feldspar) mineral grains. The intraclasts are fragments of coastal sedimentary rocks such as beachrocks, eolianites, and paleosols. The abundance percentages depend on geographic and geological factors in each coastal zone. In general, the beaches studied in La Graciosa, Lanzarote and Fuerteventura contain higher percentages of bioclasts than lithoclasts. However, volcanoclasts are more abundant than bioclasts in Gran Canaria, and sand grains of trachytic-phonolitic composition appear only on this island. Finally, urban and semi-urban beaches were found to have fewer bioclasts than natural ones.

Keywords Sandy beach · Provenance analysis · Calcareous bioclast · Volcanoclast · Intraclast · Eastern Canary Islands

Introduction

Beaches are a fundamental resource for the Canary Islands (Spain), environmentally, socially and economically. Much of the islands' economy is based on so-called "sun and beach" tourism, resulting in numerous beaches suffering intensive artificialization. Parallel to this, the remaining beach-dune systems of the islands are singular littoral ecosystems with a high degree of geo and biodiversity that occupy just 2.5% of the islands' surface area (7,447 km², Hernández-Cordero et al. 2019). Many beaches now form part of legally protected beach-dune systems which are

highly sensitive to natural processes (sea storms and floods) and anthropic activities. A sand deficit has been observed in recent years in these beach-dune systems attributable to environmental issues that have been the study of investigation by research groups of the Institute of Oceanography and Global Change (IOGAG for its initials in Spanish) of the University of Las Palmas de Gran Canaria. The specific groups in question (GEOFISMA -Physical and Environmental Geography- and GEOGAR -Applied and Regional Geology-) have focused their research on coastal areas of the eastern islands of the Canary archipelago (Cabrera-Vega et al. 2013; García-Romero et al. 2016; Alonso-Bilbao et al. 2019; Hernández-Cordero et al. 2019; Pérez-Chacón et al. 2019, among others).

One of the lines of study developed by these groups has involved the petrographic analysis of the composition of sand grains in coastal environments to determine their provenance. Such studies have been conducted principally on the islands of La Graciosa, Lanzarote, Fuerteventura and

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Gran Canaria (Alonso-Bilbao 1993; Hernández-Calvento and Mangas 2004; Alonso-Bilbao et al. 2008; Mangas et al. 2008a, b, 2017 and 2018; Cabrera-Vega 2010; Pérez-Chacón et al. 2010; García-Sanjosé 2013; Alonso-Bilbao et al. 2019; Barros 2020; Menéndez et al. 2020).

In the context described above, this work presents a bibliographic review of the petrographic results obtained by these two groups. For this purpose, a total of 50 intertidal sand samples were selected taken from 35 beaches in the eastern islands (Figs. 1, 2, Table 1). Studies were carried out on sands in La Graciosa of current beach-dune systems, in Lanzarote in the N-S Famara-Arrecife wind corridor, in Fuerteventura in the beaches of Corralejo, and in Gran Canaria on the beaches of Las Canteras to the NE of the island, in Telde to the E and in San Bartolomé de Tirajana to the S. Through this review, the aim is to discover the nature of the intertidal sands, determining the differences and similarities between samples from the same beach/island or from different islands, finding their source areas and defining the geological and geographic parameters that may generate the variability in their composition. With the above in mind, the beaches were classified as urban beaches (located in urban areas), semi-urban beaches (located in areas of medium or low population density) and natural beaches (located far from urban and semi-urban areas), following the criteria adapted for the Canary Islands by Peña-Alonso et al. (2017). Finally, the results obtained in the Canary Islands were compared with those for other beaches located in similar geotectonic environments (volcanic islands associated with oceanic intraplate hotspots).

Geological setting, materials and methods

The Canary archipelago comprises 8 islands (Fig. 1), a few islets and around 20 seamounts situated N and S of the islands. They are of magmatic origin associated with an anomaly in the Earth's mantle (hotspot) which has been active since the Jurassic (Schmincke and Sumita 2010). The subaerial volcanic materials are older in the easternmost islands, from the mid-Miocene (Fuerteventura and Lanzarote), and more recent in the westernmost islands, from the Early Pleistocene (La Palma and El Hierro). Each island edifice presents early stages of submarine volcanic construction, with subsequent subaerial emissions. In general, their genesis follows the formation model of oceanic intraplate volcanic islands, defined for the Hawaiian Islands by Walker (1990). Thus, in the subaerial formation period, they are characterized by: (i) an initial shield-building stage, with the emission of a significant amount of mafic lavas (basalts principally), followed by; (ii) an alkaline declining stage, with a smaller volume of emitted materials of felsic composition (trachybasalts, trachytes and phonolites); (iii)

an erosional stage of volcanic inactivity with the formation of sedimentary rocks (sandy and conglomerate), and finally; (iv) a rejuvenation stage of volcanic reactivation with a lower volume of mafic and, to a lesser degree, felsic rock eruptions. Sediments and sedimentary rocks are generated through the action of erosive agents contemporaneously to all the stages.

Rocky outcrops are found on the 35 beaches under study with materials from the different subaerial formation stages (Table 1, Fig. 2): mafic shield stage (MSS); felsic declining stage (FDS), and; mafic rejuvenation stage (MRS). Likewise, sedimentary rock and sediment depositions are found in these coastal areas including, for example, beachrock (Br), paleosol (Ps), eolianite (Eo), alluvial (Al) and/or colluvial (Co) deposits. Volcanic and sedimentary materials crop out both in the form of discontinuous rocky substrates on the beach itself and in nearby cliffs or on the slopes and ravines that empty into some of the beaches (Table 1, Fig. 2). In general, the materials and landforms are well preserved in these coastal areas due to the presence of a coastal cloudy desert-like climate if they are situated in northern regions with the dominance of the trade winds or of an arid climate if they are situated in the SE and S of the islands.

The 50 intertidal sand samples selected from a total of 35 beaches are distributed as shown in Fig. 1 and Table 1: 5 from La Graciosa, 9 from Lanzarote, 11 from Fuerteventura and 25 from Gran Canaria (of which 12 were taken from three sectors of Las Canteras beach, 6 from coastal beaches in the municipality of Telde and 7 from beaches in the municipality of San Bartolomé de Tirajana). Diverse geological and geomorphological elements (volcanic and sedimentary materials, landforms and structures) are found on the analyzed beaches and their surroundings which condition the nature and abundance of the sand grains.

Petrographic analyses, performed using a geological microscope with samples of sediments and sedimentary rocks, are a classical research methodology. Point counting, which involves identifying a particular number of detrital grains in a sample, is a fundamental part of the process in these studies. When the percentages of the different components are known, it is possible to perform numerical interpretations and determine the sediment source areas and the intervening factors in continental or marine depositional environments. Studies of this type were published throughout the twentieth century, but have increased in frequency over the last 50 years (Galehouse 1971; Dickinson 1985; Zuffa 1985; Kasper-Zubillaga and Dickinson 2001; von Eynatten et al. 2003; Affolter and Ingersoll 2019; among others). While there has been enormous variability in the petrographic results obtained in research studies, they have nonetheless served, among other purposes, to establish tendencies that vary according to the geotectonic environment, to characterize sediment source areas, and to determine the

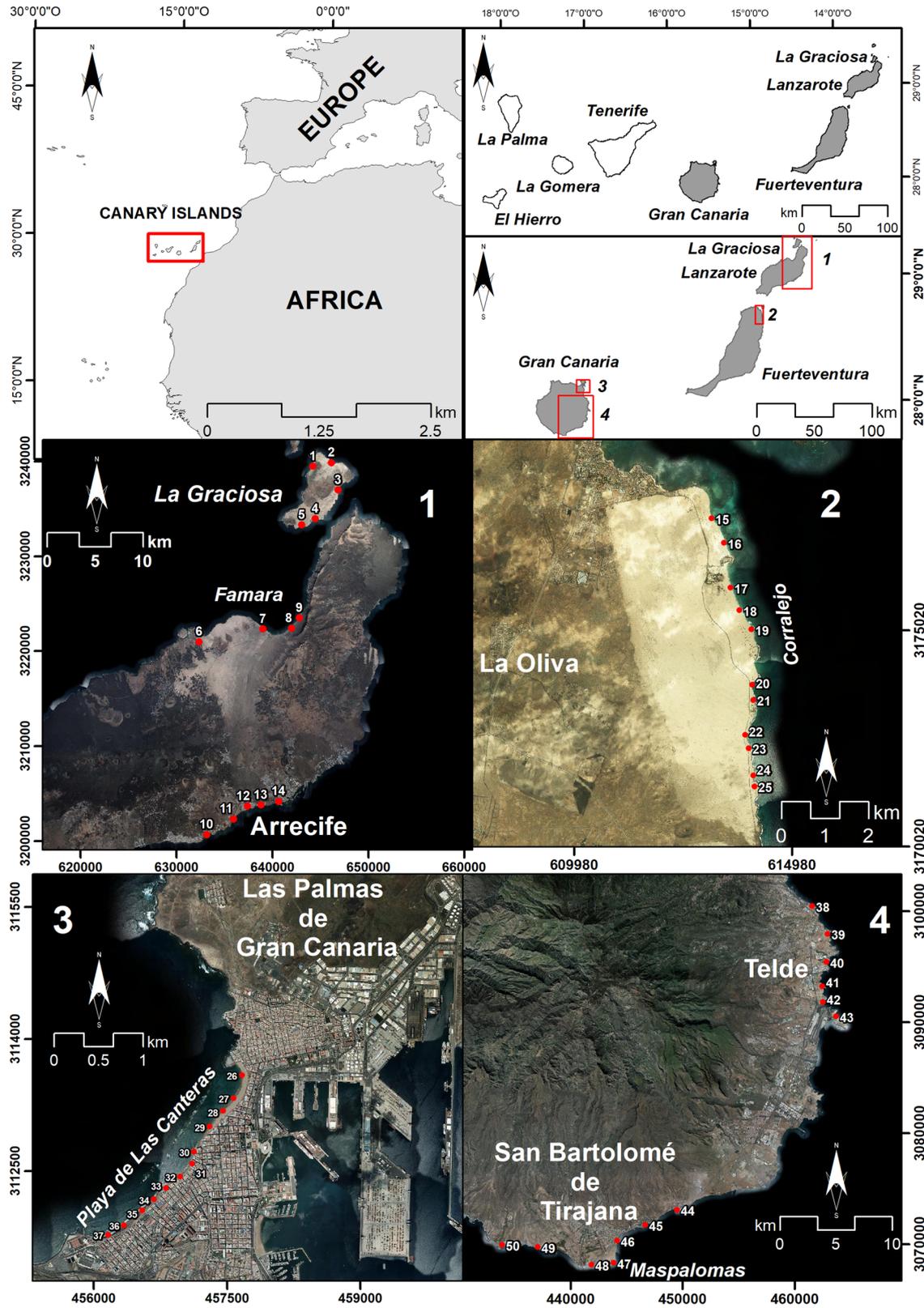


Fig. 1 Geographical location of selected beaches in the Eastern Canary Islands

Fig. 2 General view of some of the beaches studied petrographically in the eastern Canary Islands. 1) Francesa; 2) Famara; 3) Bajo Los Matos; 4) Las Canteras; 5) Aguadulce; 6) El Inglés-La Bajeta. Volcanic materials from the different formation periods: mafic shield stage (MSS); felsic declining stage (FDS), and; mafic rejuvenation stage (MRS). Sedimentary rocks and detrital sediments: beachrock (Br), paleosol (Ps), eolianite (Eo), alluvial (Al) and colluvial (Co)



physico-chemical and geological factors that intervene in the sedimentary processes. Thus, petrographic works can be found on the composition and origin of sediments of continental, marine or transitional character, and indeed from all five continents. However, very few research studies have been conducted on the provenance of sands on beaches of hotspot-associated volcanic islands, with the most notable being those by Marsaglia (1993) in Hawaii and by Le Pera et al. (2021) in Cape Verde.

The petrographic studies considered here were carried out in the Canary Islands over the course of the last 3 decades by members of the GEOGAR and GEOFISMA groups. For these studies, the methodology encompasses the following aspects: selection of study beaches according to their degree of island representativeness and prior petrographic studies, collecting sand samples, preparation of thin sections, identification of the nature of the sand grains and their relative abundance. A cross-sectional stratified sampling

(subtidal, intertidal and supratidal) was performed on the 35 selected beaches. However, in this work, only the analyses of intertidal samples taken at low tide are presented. Each sample comprised 300 g of sand, taken from the surface to a depth of 5 cm. After preparation of the thin sections, a Leitz Orthoplan microscope was used, along with a Leica-DFC420 camera and a point counter (PETROLIG). The composition of 200 grains of sand was identified for each of the thin sections, and the percentage of abundance of each type of component was calculated (14 channels). For the present work, and on the basis of the published data, comparisons were made between samples and beaches, tendencies were determined and source areas of the detrital particles present in the selected beaches were established. In addition, the governmental spatial data infrastructure (SDI Canarias) of the Canary Islands was used for the spatial analysis (geological and geographic variables, source areas, etc.) of the samples.

Table 1 Location and geology of 50 sandy samples in 35 beaches of Eastern Canary Islands

No	Beach (C cliff, R ravine)	Type	Sample	Lat. N	Lon. W	Material	
						Volcanic	Sedimentary
La Graciosa (Pérez-Chacón et al. 2010)							
1	Las Conchas (Montaña Bermeja-C)	N	GRAC-54	644,209	3,239,495	MRS	Br/Co
2	Lambra	N	GRAC-1	646,124	3,239,888	MRS	Br/Eo/Ps
3	Los Conejos (Los Conejos-R)	N	GRAC-38	646,838	3,236,995	MRS	Eo/Ps
4	Salado	S-U	GRAC-29	644,423	3,233,967	MRS	Br/Eo/Ps
5	Francesa	N	GRAC-14	643,037	3,233,333	MRS	Br/Eo/Ps
Lanzarote (Cabrera 2010)							
6	Caleta Caballo	S-U	A	632,340	3,221,000	MRS	–
7	Bajo Raso	N	7P	638,990	3,222,350	MRS	–
8	W Famara (Famara-C)	S-U	10P	641,980	3,222,430	MSS	Ps/Eo/Co
9	E Famara (Famara-C)	N	11P	642,780	3,223,530	MSS	Ps/Eo/Co
10	Los Pocillos	U	94	633,140	3,200,690	MRS	Br
11	Guasimeta	U	97	635,910	3,202,350	MRS	Br
12	Honda	U	99	637,390	3,203,700	MRS	Br
13	El Cable	U	101	638,810	3,203,830	MRS	Br
14	El Reducto	U	102	640,650	3,204,200	MRS	Br
Corralejo, Fuerteventura (García-Sanjosé, 2013)							
15	El Pozo	N	4	613,127	3,177,621	MRS	Br
16	El Médano	N	11	613,414	3,177,050	–	Br/Eo
17	Bajo Negro	N	18	613,566	3,176,013	MRS	Br
18	Larga	S-U	19B	613,769	3,175,489	–	Br
19	Bajo Los Matos	N	30	614,040	3,175,048	MRS	Br/Eo/Ps
20	N El Moro	N	31A	614,057	3,173,771	–	–
21	S El Moro	N	31C	614,089	3,173,420	–	–
22	N Alzada	N	44	613,923	3,172,500	MRS	Br
23	S Alzada	N	49	613,985	3,172,321	MRS	Br
24	N El Porís	N	34	614,122	3,171,633	MRS	–
25	S El Porís	N	35	614,091	3,171,561	MRS	Br
Las Palmas De Gran Canaria, Gran Canaria (Alonso 1993; Menéndez et al. 2020)							
26	N Las Canteras (La Puntilla-C)	U	11	457,302	3,113,006	MRS	–
27	N Las Canteras	U	12	457,453	3,113,186	–	–
28	N Las Canteras	U	13	457,572	3,113,330	–	–
29	N Las Canteras	U	14	457,666	3,113,590	–	–
30	C Las Canteras	U	A-9	457,054	3,112,544	–	Br/Ps
31	C Las Canteras	U	A-9-II	457,075	3,112,576	–	Br/Ps
32	C Las Canteras	U	A-7	456,863	3,112,384	–	Ps/Eo
33	C Las Canteras	U	A-7-III	456,893	3,112,403	–	Ps/Eo
34	S Las Canteras	U	1	456,193	3,111,792	–	–
35	S Las Canteras (La Ballena-R)	U	2	456,302	3,111,857	FDS/MRS	Al
36	S Las Canteras (La Ballena-R)	U	4	456,569	3,112,087	FDS/MRS	Al
37	S Las Canteras	U	5	456,709	3,112,243	–	–
Telde, Gran Canaria (Mangas et al. 2018; Burgoa 2019)							
38	Malpaso (Bocabarranco-C)	S-U	TEL-37	461,544	3,100,472	MRS	Al/Eo/Ps
39	La Garita (La Garita-C)	S-U	TEL-16	462,915	3,097,981	MRS	Al/Ps
40	Salinetas (Sacateclas-R)	S-U	Sal-6	462,799	3,095,455	MRS	Al/Br/Eo
41	Aguadulce (Esquila-R)	N	TEL-12	462,433	3,093,244	MRS	Br/Eo/Ps
42	Ojos de Garza (Draguillo-R)	S-U	TEL-14	462,500	3,091,810	MRS	Al/Eo/Ps
43	Ámbar (Montaña del Ámbar-C)	N	TEL-22	463,668	3,090,541	MRS	Br/Eo/Ps

Table 1 (continued)

No	Beach (<i>C</i> cliff, <i>R</i> ravine)	Type	Sample	Lat. N	Lon. W	Material	
						Volcanic	Sedimentary
San Bartolomé De Tirajana, Gran Canaria (Hernández & Mangas 2004; Alonso et al. 2008)							
44	Tarajalillo (Berriel-R)	S-U	112-B	449,498	3,073,107	FDS/MRS	Al/Ps
45	San Agustín (San Agustín-R)	U	113-B	446,677	3,071,739	FDS	Al
46	El Inglés (Buenavista-R)	U	114-B	444,138	3,070,322	FDS	Al
47	Punta La Bajeta	N	A-6	443,831	3,068,322	–	–
48	Maspalomas (Fataga-R)	U	108-B	441,862	3,068,149	FDS/MRS	Al/Br/Ps
49	Montaña Arena (Montaña Arena-C)	N	107-B	437,069	3,069,750	FDS	Al/Eo/Co
50	El Pajar (El Pajar-C)	U	105-B	433,882	3,069,944	FDS/MRS	–

U Urban beaches, *SU* semi-urban beaches, *N* natural beaches. Volcanic material mafic shield stage *MSS* felsic declining stage *FDS* and mafic rejuvenation stage *MRS*. Sedimentary material: beachrock *Br*, paleosol *Ps*, eolianite *Eo*, alluvial *Al* and colluvial *Co*

Results

The results are presented showing first the geological and geographic characteristics of the 35 selected beaches under study in the 4 islands (Table 1), followed by the petrographic data and the percentages of the abundance of the components of the samples (Table 2). The treatment of the data allows; i) determination of tendencies between sectors of the same beach, between beaches of the same island and between islands in terms of the nature and abundance of the components of the samples; and ii) definition of the similarities and differences between samples.

Geological and geographic characteristics of the beaches under study

Easternmost canary islands

The islands of La Graciosa, Lanzarote and Fuerteventura (Fig. 1; Table 1) form part of a single oceanic intraplate volcanic edifice (Acosta et al. 2005; Schmincke and Sumita 2010), oriented in a NE-SW direction. This edifice, which rises from a depth of 4000 m, constitutes a well-developed insular platform as these are old islands undergoing a dismantling process. The subaerial volcanic rocks present ultramafic and mafic (UM-M) and, to a lesser extent, felsic (F) geochemical compositions from the MSS formation stage (basanites, tephrites, basalts and trachybasalts) and associated with Miocene polygenetic volcanoes, of which only eroded remains of hundreds of meters of thickness are preserved today. There are additionally scattered Plio-Quaternary (<5 Ma) monogenetic edifices from the MRS of these islands which emitted meters-thick lava flows and pyroclastic fall UM-M deposits.

The island of La Graciosa (surface area of 20 km²) was formed by strombolian and hydromagmatic activity with UM-M materials from the mid-upper Pleistocene. Its genesis

is related to the Miocene MRS of the polygenetic Famara volcano on the neighboring island of Lanzarote. La Graciosa is of hilly relief, with volcanic cones < 170 m in height which are covered by eolian blankets, eolianites and paleosols (Pérez-Chacón et al. 2010; Mangas et al. 2017). The five beaches under study are coves hundreds of meters long with beige-colored medium-grain sands. Scattered rocky substrates can be found, formed from UM-M lava flows or beachrock, paleodunes and paleosols (Table 1, samples 1–5; Fig. 2A). Of the five beaches studied, four are natural and one semi-urban (sample 4). Overall, La Graciosa has three beach-dune systems, two moderately active (samples 1–2) and one currently stabilized (samples 3–5). The historical and present anthropic uses are among the causes of this stabilization (Santana-Cordero et al. 2016b) as they have substantially altered the eolian dynamics. Today, the island has a protected status, forming part of the Natura 2000 network (Directive 92/43/EEC 1992), and there has been a significant increase in recent years in plant cover. However, the island is subject to strong tourism pressure, with an increase in recent decades of built-up land in the center of Caleta del Sebo (García-Romero et al. 2016), one of the areas through which sediment enters from the direction of the sea to the eolian system in the S of the island. Together with sediment stabilization due to plant recolonization (Santana-Cordero et al. 2016b), this explains the observation of a sediment deficit in the sediment exit point of this system (sample 4).

With respect to the island of Lanzarote, a total of nine samples were subjected to petrographic analysis: four from close to Famara village to the N of the island and five to the Arrecife, the island's capital (Table 1, Fig. 1). Famara beach is part of a beach-dune system that has been active since the Quaternary, as is shown by tens-of-meters thick eolianite layers situated inshore, although it is currently almost stable (Cabrera-Vega 2010). This beach, and its surroundings, constitute the entrance area of cream-colored medium-grain-sized sandy sediments. In the past, these sediments

Table 2 Abundance (%) of different components of sands from beaches of the Eastern Canary Islands

No	Beach	Sample	Bioclasts			Intracl	Lithoclasts				
			Flora	Fauna	Total		M-min	MR-fr	F-min	FR-fr	Total
La Graciosa (Pérez-Chacón et al. 2010)											
1	Las Conchas	GRAC-54	49.6	32.3	81.9	10.6	5.0	2.5	0	0	18.1
2	Lambra	GRAC-1	53.9	33.2	87.1	9.3	1.0	2.6	0	0	12.9
3	Los Conejos	GRAC-38	47.9	37.6	85.5	8.0	0	0	0	0	14.5
4	Salado	GRAC-29	33.7	34.9	68.6	7.9	2.9	20.6	0	0	31.4
5	Francesa	GRAC-14	44.0	33.1	77.1	8.6	2.3	12.0	0	0	22.9
Lanzarote (Cabrera, 2010)											
6	Caleta Caballo	A	22.7	52.8	75.5	9.9	3.0	11.6	0	0	24.5
7	Bajo Raso	7P	19.3	60.7	80.0	12.5	0.6	6.9	0	0	20.0
8	W Famara	10P	14.3	47.9	62.2	8.9	4.0	24.9	0	0	37.8
9	E Famara	11P	13.6	46.3	59.9	8.3	2.6	29.2	0	0	40.1
10	Los Pocillos	94	13.6	22.3	35.9	5.3	9.2	49.6	0	0	64.1
11	Guasimeta	97	13.0	29.2	42.2	6.5	4.4	46.9	0	0	57.8
12	Honda	99	12.3	33.5	45.8	2.3	6.0	45.9	0	0	54.2
13	El Cable	101	9.0	21.6	30.6	2.6	3.6	63.2	0	0	69.4
14	El Reducto	102	23.6	45.6	69.2	8.9	2.4	19.5	0	0	30.8
Corralejo, Fuerteventura (García-Sanjosé, 2013)											
15	El Pozo	4	36.3	49.6	85.9	11.7	1.4	0.3	0	0	14.1
16	El Médano	11	37.6	57.0	94.6	4.7	0	0.7	0	0	5.4
17	Bajo Negro	18	43.0	49.7	92.7	6.6	0	0.7	0	0	7.3
18	Larga	19B	26.3	58.7	85.0	15.0	0	0	0	0	15.0
19	Bajo Los Matos	30	30.0	64.3	94.3	5.7	0	0	0	0	5.7
20	N El Moro	31A	45.0	47.3	92.3	7.0	0.7	0	0	0	7.7
21	S El Moro	31C	43.7	43.3	87.0	12.0	0.7	0.3	0	0	13.0
22	N Alzada	44	36.8	52.3	89.1	10.3	0.6	0	0	0	10.9
23	S Alzada	49	42.3	47.3	89.6	8.7	1.0	0.7	0	0	10.4
24	N El Porís	34	39.0	53.4	92.4	7.0	0.6	0	0	0	7.6
25	S El Porís	35	43.3	48.4	91.7	7.7	0.6	0	0	0	8.3
Las Palmas De Gran Canaria, Gran Canaria (Alonso 1999; Menéndez et al. 2020)											
26	N Las Canteras	11	N.D	N.D	39.9	4.1	1.3	25.2	7.8	30.7	60.0
27	N Las Canteras	12	N.D	N.D	41.3	7.3	2.2	24.4	9.8	27.0	58.6
28	N Las Canteras	13	N.D	N.D	51.3	3.2	4.5	22.6	6.8	22.9	48.7
29	N Las Canteras	14	N.D	N.D	45.1	7.0	5.2	27.2	9.3	20.6	54.8
30	C Las Canteras	A-9	15.8	21.3	37.1	16.2	0.7	3.5	7.8	43.2	62.9
31	C Las Canteras	A-9-II	29.6	12.5	39.8	20.3	11.8	18.3	9.2	21.6	60.2
32	C Las Canteras	A-7	30.1	13.5	43.6	7.5	18.1	19.6	7.5	29.3	56.4
33	C Las Canteras	A-7-III	30.3	12.1	42.4	10.7	25.5	31.8	7.2	15.1	57.6
34	S Las Canteras	1	N.D	N.D	33.8	3.3	29.2	52.6	2.5	10.3	66.2
35	S Las Canteras	2	N.D	N.D	42.7	1.7	25.1	45.8	4.4	9.9	57.3
36	S Las Canteras	4	N.D	N.D	47.0	5.2	16.0	34.9	5.0	12.9	53.0
37	S Las Canteras	5	N.D	N.D	42.3	4.6	13.2	33.1	6.6	20.0	57.7
Telde, Gran Canaria (Mangas et al. 2018; Burgoa 2019)											
38	Malpaso	TEL-37	13.0	7.0	20.0	0	12.0	42.0	10.5	38.0	80.0
39	La Garita	TEL-16	6.5	4.0	10.5	0.5	23.0	71.0	6.0	18.0	89.5
40	Salinetas	Sal-6	5.0	17.0	22.0	7.0	25.5	62.0	3.5	9.0	78.0
41	Aguadulce	TEL-12	32.0	20.5	52.5	0	10.0	37.5	9.0	10.0	47.5
42	Ojos de Garza	TEL-14	16.5	15.0	31.5	10.5	17.0	47.0	8.5	11.0	68.5
43	Ámbar	TEL-22	47.0	18.0	65.0	6.5	8.5	24.5	0.5	4.0	35.0

Table 2 (continued)

No	Beach	Sample	Bioclasts			Intracl	Lithoclasts					
			Flora	Fauna	Total		M-min	MR-fr	F-min	FR-fr	Total	
San Bartolomé De Tirajana, Gran Canaria (Hernández & Mangas 2004; Alonso et al. 2008)												
44	Tarajalillo	112-B	12.3	6.2	18.5	1.6	9.0	36.3	8.6	43.6	81.5	
45	San Agustín	113-B	10.3	7.5	17.8	1.3	31.0	56.3	6.3	24.6	82.2	
46	El Inglés	114-B	18.3	11.2	29.5	2.3	1.3	16.6	9.6	51.6	70.5	
47	Punta La Bajeta	A-6	30.3	13.4	43.9	7.3	N.D	13.9	N.D	34.9	56.1	
48	Maspalomas	108-B	23.6	15.0	38.6	2.3	9.3	22.9	8.6	36.2	61.4	
49	Montaña Arena	107-B	9.3	8.4	17.7	0.8	13.0	31.2	9.0	50.3	82.3	
50	El Pajar	105-B	2.0	8.5	10.5	0.6	5.6	20.9	18.0	68.0	89.5	

Flora red algae, *Fauna* mollusks, echinoderms foraminifera bryozoans. *Intracl* intraclasts. *M-min* mafic mineral, *MR-fr* mafic rock fragment, *F-min* felsic mineral, *FR-fr*, felsic rock fragment. *N.D* No data

passed through a wind corridor which, after crossing the island over some 20 km, exited via various beaches of darker colored sands situated between Arrecife to the N and Puerto del Carmen to the S. In the last few decades, the dunes have disappeared in the wind corridor and the eolian blanket has become almost stabilized. The sand samples were taken from eight beaches with differing materials and geomorphologies (Mangas et al. 2008b; Cabrera-Vega 2010). For example, Famara beach (samples 8–9) is next to hundreds-of-meters high paleocliffs formed by the piling of UM-M lava flows from the Famara shield volcano (between 10.2 and 3.7 Ma). These eroded volcanic remains have sharply descending slopes, forming several generations of colluvial and eolianite deposits lower down (Fig. 2B). Found on the beach situated close to Famara village are discontinuous outcrops of layers of Holocene beachrock (Mangas et al. 2008b). The sandy beaches located to the W of Famara village (samples 6–7) overlie lava and pyroclastic materials (of the MRS) from the lower and mid-Pleistocene (< 1.8 Ma). As for the beaches south of Arrecife (samples 10–14), these are also found over lava and pyroclastic materials from the lower and mid Pleistocene (MRS), associated with diverse volcanic complexes and strombolian fissure vents. These volcanic materials crop out in the form of the remains of rocky substrates on the beaches, or cliffs a few meters high, along with layers of beachrock from the upper Pleistocene and Holocene. The Famara cliffs, as well as a large stretch of its littoral and contiguous marine area are under protected status, forming part of the Natura 2000 network. Of the beaches studied, two are natural (samples 7 and 9) and two semi-urban (samples 6 and 8), close to the village and tourist developments. However, the five beaches in the Arrecife area have been classified as urban (samples 10–14) as they are found in residential or tourist zones.

In the NE of the island of Fuerteventura samples from ten beaches were subjected to petrographic analysis (Table 1,

samples 15–25; Fig. 1 and Fig. 2C). These beaches are situated in the coastal region of the Dunas de Corralejo Nature Reserve (part of the Natura 2000 network). This protected area comprises an active beach-dune system which presents signs of sediment deficit after construction work in the area where sediments enter from the direction of the sea. The dunes and eolian blankets have lost volume, probably as a result of anthropogenic alterations (Fernández-Cabrera et al. 2011; Malvárez et al. 2013). According to García-Sanjosé (2013), the light beige-colored beach and eolian sands of medium grain size lie over coastal sedimentary deposits of beachrock, eolianites and paleosols from the Upper Pleistocene and Holocene, and over basalt lava flows from the mid-Pleistocene (MRS). There is a notable difference between the northernmost and southernmost sectors of this eolian system. Whereas in the former there is presently a predomination of sand sheets and hummock dunes, towards the south free landforms appear, including barchan dunes some 3 m high on their slip face or barchan ridges of short length. The limits of each of the studied beaches correspond to outcrops of volcanic and/or sedimentary rocks which appear along the coast (Fig. 1). All the beaches are natural, except for Larga beach (Table 1, sample 18), which is classified as semi-urban given its proximity to tourist complexes.

Gran Canaria island

The island of Gran Canaria is highly geodiverse, with a geological history of around 14.5 Ma (Acosta et al. 2005; Schmincke and Sumita 2010). The igneous and sedimentary materials that form the island are related to the construction stage of the Tejeda stratovolcano (MSS), with a volume of UM-M materials of approximately 1000 km³ emitted between 14.5 and 14.1 Ma. This stage was followed by a long alkaline declining stage (FDS), with the eruption of F rocks between 14.1 and 7.4 Ma of a volume of around 1000

km³. There was a subsequent period of volcanic inactivity of around 2 million years, with the erosion of materials of the Tejada stratovolcano and the formation of alluvial deposits. Finally, we have the MRS, which dates from 5.5 Ma to the present day, with the eruption of UM-M and, to a lesser degree, F materials of a volume of around 200 km³. In the coastal areas of the island, we find alluvial, colluvial, beachrock, eolianite and paleosol morphologies and sedimentary deposits from different epochs. Most of the sandy beaches of the islands are situated along the E and S coasts, with occasional instances in the N and NE. The beaches are associated with bays sheltered by rocky projections and to ravine mouths (Alonso-Bilbao 1993; Menéndez et al. 2008, 2020; Alonso-Bilbao et al. 2019). Gran Canaria is heavily populated, with 43% of its landforms altered by human activity (Ferrer-Valero et al. 2017), especially the coastal dunes, paleodunes and beaches.

A total of 25 geologically and geomorphologically highly diverse samples were analyzed, corresponding to 14 beaches (Table 1, Fig. 1). The urban beach of Las Canteras (Table 1, samples 26–37; Fig. 2D), with cream-colored medium-grain sized sands, can be divided into three sectors (northern, central and southern—N, C and S). In the N sector is a cliff formed by basalt lava flows from the mid Pleistocene (MRS), in the C sector are scattered outcrops of Holocene beachrock, paleosols and eolianites, both along the beach and reef, and in the S sector is the mouth of the La Ballena ravine, which in periods of torrential rainfall transports sediment to the beach (Alonso-Bilbao 1993). The slopes of these ravines vary in terms of the materials' composition and ages. Thus, F lava flows (FDS) are found in the lower sections, followed by alluvial deposits from the island's erosional stage and culminating in UM-M lavas and pyroclasts (MRS). Until the first half of the twentieth century, Las Canteras beach was the sandy sediment input area to a beach-dune system that had functioned during the Holocene. The sediments in the backshore zone used to form a dunefield and eolian blankets in the Guanarteme isthmus and exited through Las Alcaravaneras beach to the E. After the construction of Las Palmas de Gran Canaria city was extended along the isthmus, the aeolian dynamics of the beach-dune system were completely altered (Santana-Cordero et al. 2016a). For this reason, Las Canteras beach presents irregular sedimentary balances over time, with areas of sand gain in subtidal and intertidal sectors and other areas of sand loss where the Holocene sedimentary rocky substrate crops out.

The six selected beaches along the coast of the municipality of Telde (Table 1, samples 38–43; Fig. 2E; Mangas et al. 2008a, 2018; Burgoa 2019) are characterized by the accumulation of medium-grain sands and are situated in small bays located between rocky projections and cliffs tens of meters high (sample 38–40 and 42) made from the piling of UM-M lava flows (MRS). There also appear on some

of these beaches conical strombolian edifices and pyroclastic fall deposits (samples 41 and 43). Commonly, there are sedimentary beachrock, eolianites, paleosols and alluvial deposits, both on the beaches and their surroundings. Small ravines, with beds hundreds of meters or a few kilometers long, empty out into the beaches of Salinetas, Aguadulce and Ojos de Garza (samples 40–42), with predominantly Plio-Quaternary UM-M volcanic material (MRS). However, in the surroundings of Malpaso beach (38), on the northern coast of the municipality, local felsic Miocene (FDS) and Pliocene (MRS) materials crop out. In general, the beaches are semi-urban, except for Aguadulce beach which is in a protected area (Tufia Area of Scientific Interest), and Ámbar beach which is situated in the restricted military area of Gando, close to Gran Canaria airport.

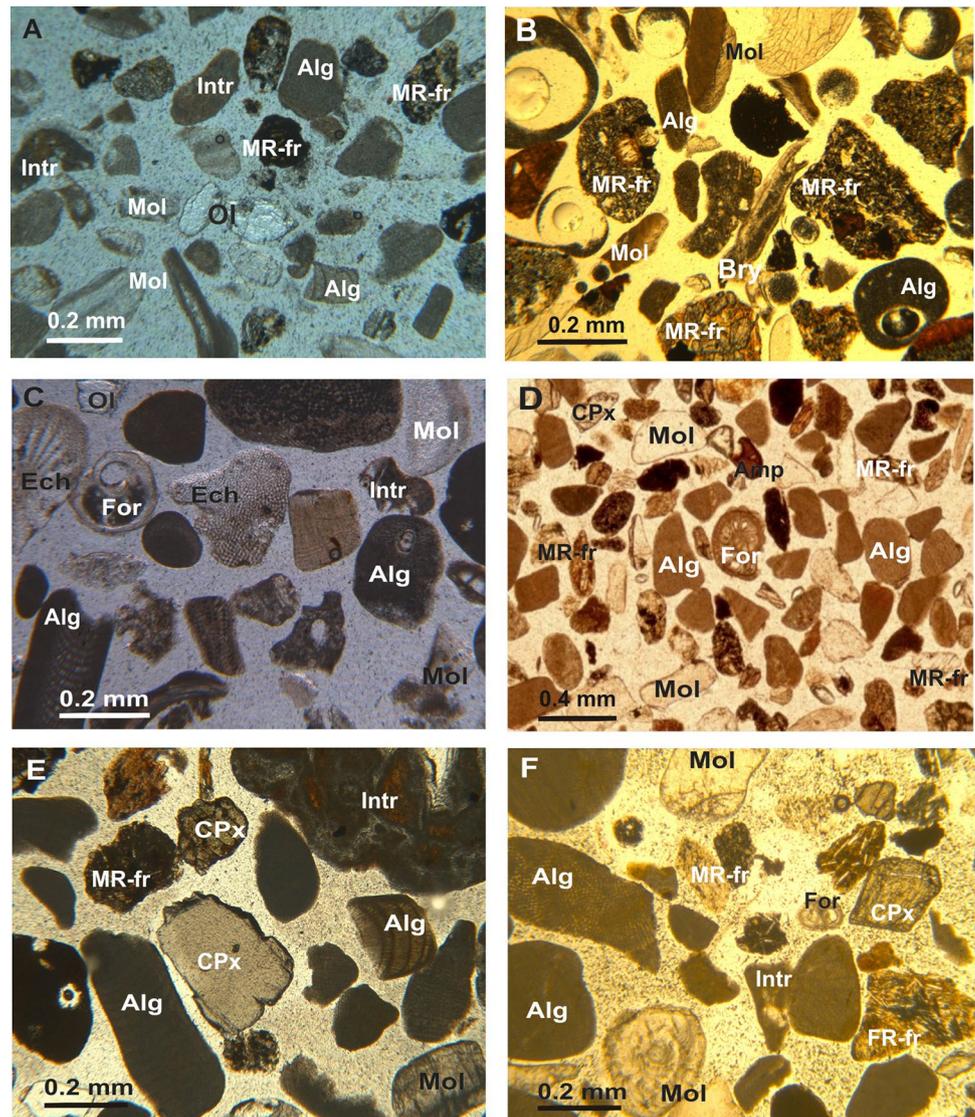
Finally, seven beaches were selected for study in the S of the island (Table 1, samples 44–50) in the municipality of San Bartolomé de Tirajana. Of these, two are classified as natural (47 and 49), one semi-urban (44) and the rest as urban. The beaches are characterized by their brown-colored medium-grain sandy deposits (Alonso-Bilbao et al. 2008). Four of the beaches are small, just a few hundred meters long (samples 44–45 and 49–50), whereas the three beaches of the Dunas de Maspalomas Special Nature Reserve (samples 46–48) are kilometers long and their sands are beige in tone. The latter beaches form part of an active beach-dune system whose sediments enter from the direction of the sea through El Inglés beach to the N (Fig. 2F), forming a dunefield and eolian blankets, and exit to the S through Maspalomas beach. This complex is threatened by the tourist development that began in the 1960s and has significantly altered the eolian dynamics and the ecology of the beach-dune system (Hernández-Calvento 2006; Hernández-Cordero et al. 2017, 2018; García-Romero et al. 2019). In most of the beaches studied, there appear rocky substrates and cliffs a few meters high formed by Miocene volcanic F rocks (FDS) and alluvial sediments from the erosive stage. Except for the beaches of Montaña Arena and El Pajar (samples 49–50), the rest are situated in ravine mouths whose beds lie over Miocene (FDS) and Pliocene (MRS) rocks of F composition. In the surroundings of many of these beaches there are also alluvial sediments, and paleosols, eolianites and beachrock deposits.

Petrography of the sands and percentages of the abundance of their components

The microscopic identification of the sand grains allowed three types of component to be identified; lithoclasts, intra-clasts and bioclasts. Point counting in each thin section allowed estimation of the abundance percentage of each type (Table 2, Fig. 3).

The volcanic lithoclasts that were identified are rock fragments, both UM-M and F, formed of volcanic glass,

Fig. 3 Geological microscope photographs of thin sections of beach sand in different beaches analyzed in the eastern Canary Islands. **A** Francesa (S of La Graciosa); **B** Famara (NW of Lanzarote); **C** Bajo Los Matos (Corralejo, NE of Fueteventura); **D** N Las Canteras (NE of Gran Canaria); **E** Aguadulce (Telde, E of Gran Canaria); **F** Playa del Inglés (S.B. of Tirajana, S of Gran Canaria). Identification of detrital grains: Alg: red algae; Mol: mollusks; Ech: echinoderms; For: foraminifera; Bry: bryozoans; Intr: intraclasts; Ol: olivine; CPx: clinopyroxene; Amp: amphibole; Fel: feldspar; MR-fr: mafic rock fragment; FR-fr: felsic rock fragment



a microcrystalline matrix and fine (< 1 mm) to medium (1–5 mm) sized crystals. The textures of the UM-M rock fragments (basanites, tephrites and basalts) are microporphyritic and porphyritic. In contrast, those of the F fragments (trachybasalts, trachytes and phonolites) are micro-litic, lathwork and fluidal. The crystals in the rock fragments and the individual grains are olivine, clinopyroxene, amphibole, Fe-Ti oxides, aegirine, plagioclase and alkaline feldspars. The volcanoclastic grains come from the erosion of lavas and pyroclasts from the MSS, FDS and MRS, and have differing degrees of alteration. In this study, clasts have been differentiated only according to their nature (rocks and individual minerals) and these in turn by their M and F petrologic composition (Table 2).

The intraclasts are comprised of volcanic, sedimentary and bioclast fragments, and micrite and sparite carbonate

cement. There are simple intraclasts of just one component and complex intraclasts of various components, plus carbonate cement. The Holocene intraclasts do not present signs of component alteration, with the oldest reddish and blackish in tone due to Fe and Mn oxides. However, only the intraclast grains were considered, without differentiation regarding their nature or alterations.

The bioclast sand grains are formed principally of the remains of marine flora and fauna, with fragments of red coralline algae and mollusks predominating and, to a lesser extent, foraminifera, echinoderms and bryozoans. The marine fauna and flora inhabit the insular platforms and subtidal zones and, when they die, their remains are transported to the intertidal and supratidal zones where they break into pieces and decompose.

Easternmost canary islands

The petrographic results from the 25 intertidal sand samples obtained from the islands of La Graciosa, Lanzarote and Fuerteventura are shown in Table 2. The beaches of La Graciosa reveal a predominance of bioclasts over lithoclasts (Figs. 3A, 4A and 5A), with notable percentages of the abundance of red algae followed by molluscs. The values of UM-M rock fragments (MR-fr) and ferromagnesian minerals (M-min) present small percentages, with the lowest (<6%) being those of the foraminifera, echinoderms and bryozoans (Pérez-Chacón et al. 2010 and Mangas et al. 2017). The % distribution varies by beach, with Lambra (sample 2) having the highest in flora grains (53.9%), and Los Conejos ravine (sample 3) in fauna (37.6%). Total bioclasts predominate in the five beaches, with the highest percentage in sample 3 (85.5%) and the lowest in Salado beach (sample 4) with 68.6%. Higher percentages are found in the N and E beaches compared to those of the S. The intraclast and volcanoclastic data (MR-fr and M-min) have low values, with the former higher than the latter (Fig. 5C).

The eight beaches studied in Lanzarote show differences in the abundance of their components (Table 2, Figs. 3, 4, 5A, C) between the beaches of the N (samples 6–9) and those of the S (samples 10–14). Those of the N have higher bioclast grain values, whereas in those in the S, there is a higher content of volcanoclastic sands than bioclasts. Among the bioclasts, mollusc grains predominate over algae (Fig. 5A), while there is a very low proportion (<2%) of foraminifera, echinoderms and bryozoans (Cabrera-Vega 2010). In all the beaches, the MR-fr values are higher than those for M-min, and both in turn are higher than the intraclast values, except for Bajo Raso beach (sample 7; Fig. 5C, Table 2).

Finally, there is notable homogeneity in the composition of the sands of the beaches of Corralejo (Fuerteventura), with the highest bioclast values observed on beaches studied in the eastern islands (García-Sanjosé 2013). The samples show moderate intraclast values and very low values in volcanoclastic sands (Table 2; Figs. 3C and 5C). The marine fauna values are higher than those for flora, and are between the values observed in the islands of La Graciosa and Lanzarote (Fig. 5A). The percentages of intraclast grains are

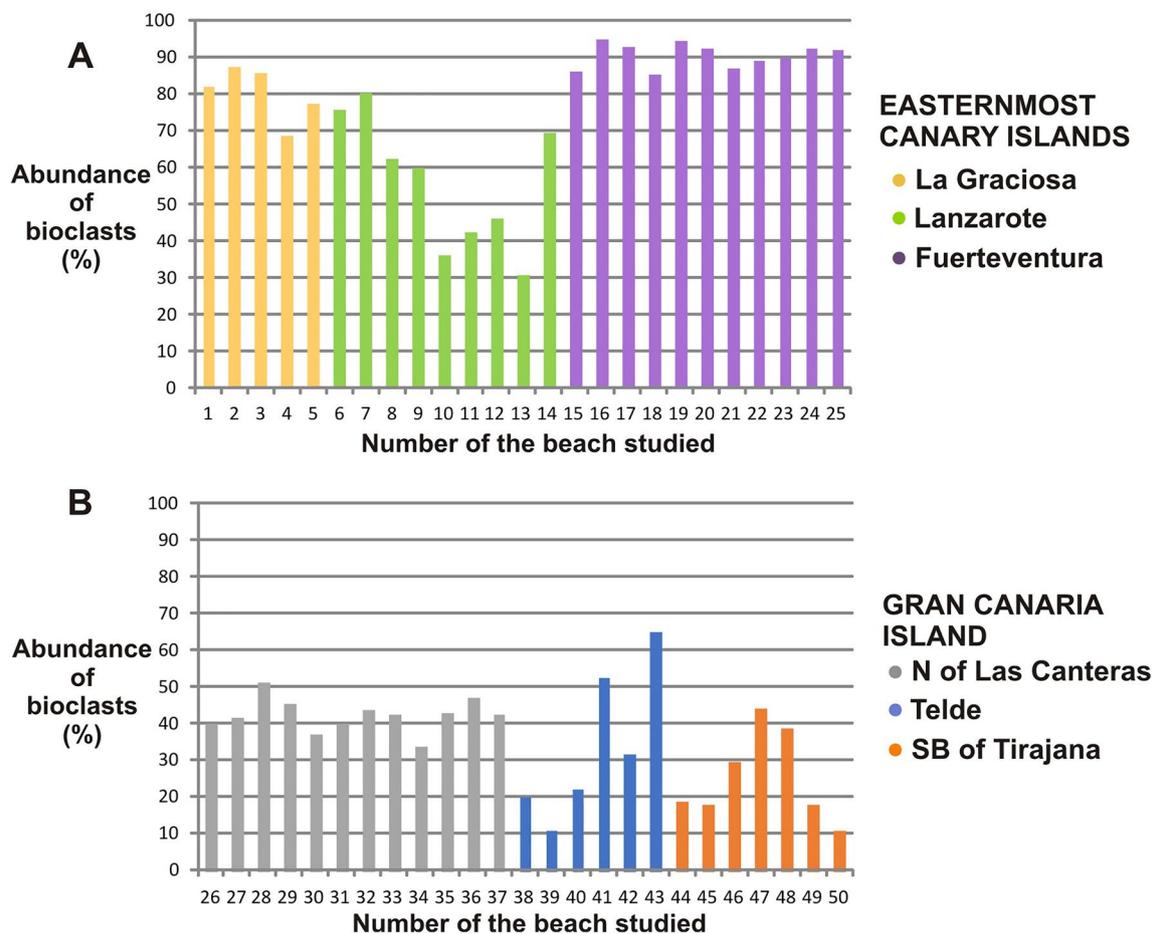
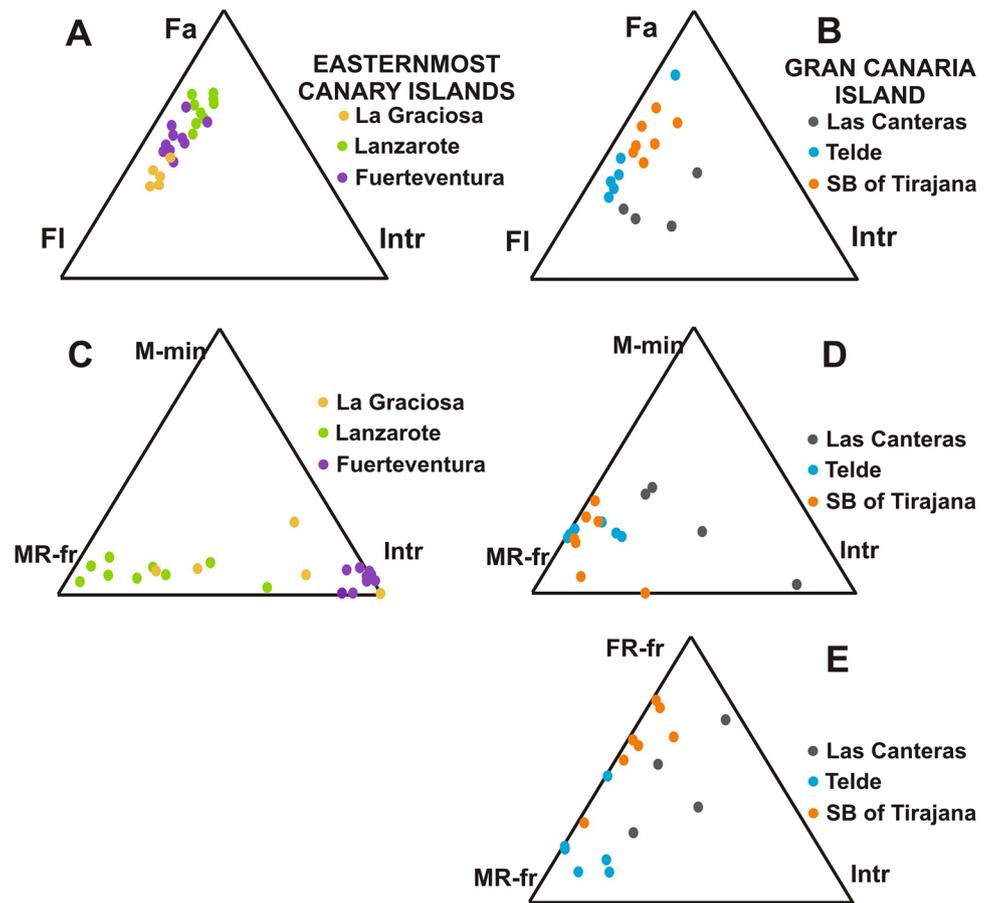


Fig. 4 Histograms with bioclast abundance values (%) in the easternmost Canary Islands (La Graciosa, Lanzarote and Fuerteventura) and Gran Canaria (Table 2). The numbers along the x-axis are the codes of the studied beaches (Table 1)

Fig. 5 Triangles with the petrographic data of the 35 beaches studied in the easternmost Canary Islands (La Graciosa, Lanzarote and Fuerteventura) and Gran Canaria. FI: flora, Fa: fauna, Intr: intraclasts, MR-fr: mafic rock fragments, M-min: mafic minerals, FR-fr: felsic rock fragments



in all cases higher than those of the volcanoclastic sands (Fig. 5C), and are the highest observed in these eastern islands.

Gran Canaria island

The 25 samples studied from the island of Gran Canaria (Fig. 1, Table 2) correspond to 3 coastal zones: Las Canteras beach (samples 26–37) in the NE; the beaches of Telde (samples 38–43) in the E; and those of San Bartolomé de Tirajana (samples 44–50) in the S.

Three sectors (N, C and S) were considered in Las Canteras beach, using the petrographic data from Alonso-Bilbao (1993) and Menéndez et al. (2020). In general, there is a higher abundance of volcanoclastic vs. bioclastic grains in all three sectors (Table 2, Figs. 3D, 4B), although with slight variations. Among the volcanoclastics, the MR-fr predominates over the M-min (Fig. 5D) in all the samples, while the FR-fr predominate over the MR-fr only in most of the San Bartolomé de Tirajana and Las Canteras samples (Fig. 5E), except in some samples from the N and C sectors, while the presence of M-min is minimal except in some samples from sectors C and S. With respect to the bioclasts, there are higher percentages of red algae vs. mollusc grains (Fig. 5B),

while the percentages of foraminifera, echinoderms and bryozoans are very small. The abundance of intraclasts in the samples is low, with the highest values found in sector C.

An analysis of the petrographic data for the beaches of Telde (Table 2, Fig. 3E, Fig. 5B, D, E, Fig. 4B) shows that in those in the N of Telde, namely Malpaso, La Garita, Salinetas and Ojos de Garza (samples 38–40 and 42) there is a predominance of volcanoclastic MR-fr and M-min sand grains (> 68.5%), with the highest value obtained in La Garita of almost 90%, while the values for FR-fr and F-min lithoclasts are lower except in Malpaso beach (Mangas et al. 2018). The bioclast percentages are over 50% in the beaches of Agudulce and Ámbar (Figs. 3E, 5B) in the S of the municipality, with red algae values higher than those for molluscs in all the beaches studied, except for Salinetas, while the values for foraminifera, echinoderms and bryozoans are very low (< 1.5%). The percentages of the abundance of intraclast grains are low, less than 10% (Fig. 5B, D, E), with those from the samples from Ojos de Garza and Ámbar being the highest, followed by those from Agudulce and Salinetas, while the lowest values are from La Garita and Malpaso.

With respect to the petrogenetic results from the beaches of the coast of San Bartolomé de Tirajana (Hernández-Calvento and Mangas 2004; Alonso-Bilbao et al. 2008),

lithoclasts predominate over bioclasts, with a notable presence of volcanoclastics in Pajar beach (sample 50) with a maximum value of 89.5% (Table 2; Figs. 3F, 4B). Among the terrigenous volcanic components, the FR-fr and F-min predominate in all the beaches, with values ranging between 45 and 86%, except in San Agustín beach (sample 45) where there is a higher abundance of MR-fr (Table 2, Fig. 5E). These are followed in % terms by UM-M rock grains and, to a lesser extent, by ferromagnesian minerals, both from the MRS (Fig. 5D). The abundance values of bioclast fragments are moderate to low, with a predominance of flora over fauna grains (Fig. 5B), except in El Pajar beach. Finally, intraclast values are low, less than 7%, with the highest values found in Maspalomas (samples 46–48).

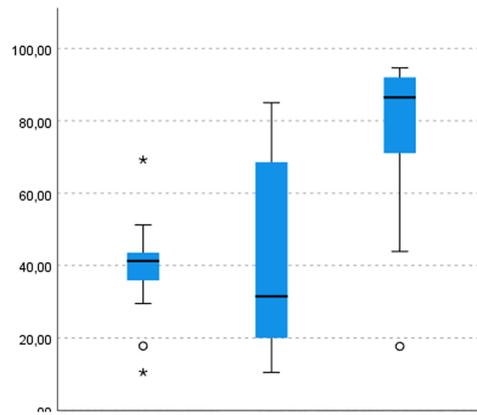
Discussion

An inter-beach analysis and comparison of the petrographic results of the different Canary beaches under study were made, and the results were additionally compared with those from other hotspot-associated volcanic islands (Hawaii and Cape Verde).

The petrographic results of the Canary beaches reveal that the presence of certain sand grains and their abundance are related to geological and geographic elements and to natural and anthropic processes. The MR-fr volcanoclastic sand grains, with porphyritic texture and altered M-min, originate in polygenetic volcanoes (MSS), as can be observed in the beaches of Famara in Lanzarote. Likewise, the presence of FR-fr and F-min volcanoclastic sands, with trachytic and fluidal textures, is found on beaches close to outcrops of FDS materials as, for example, in the beaches of Gran Canaria (Las Canteras and San Bartolomé de Tirajana). The presence of MR-fr and M-min grains, with porphyritic and microporphyritic textures and low levels of alteration, is related to beaches close to MRS monogenetic volcanoes as, for example, in the beaches of La Graciosa, Corralejo, the S of Lanzarote, Telde and, to a lesser extent, the N de Lanzarote and NE and S of Gran Canaria. If a comparison is made with the beaches studied in the islands of Hawaii (Marsaglia 1993) and Cape Verde (Le Pera et al. 2021), it can be seen that altered volcanoclastic sands appear in the oldest islands, while glassy grains are fundamentally found in the younger islands. However, in the Canary Islands, the presence of these sands of altered lithoclasts is not related to island age, but rather to the existence of remains of polygenetic Miocene volcanoes close to the beaches. Moreover, the islands of Hawaii and Cape Verde have a high frequency of glassy grains generated in subaerial and submarine eruptions (hyaloclastites). In contrast, in the Canaries, this type of grain is very rare or non-existent. Likewise, the M-min grains of Canary beaches are low in abundance except in

some samples (Las Canteras, N of Telde and N of San Bartolomé), whereas in Cape Verde and Hawaii, higher abundance values are found. In the analysis of volcanogenic grains in various parts of the world conducted by Affolter and Ingersoll (2019), it was found that lathwork textures predominate for grains of mafic composition, microlitic textures for felsic sands and granular textures for acidic sands. These lathwork textures are recorded for Hawaii and Cape Verde, but in the Canaries are very scarce as the polygenetic volcanoes have very few MSS feldspar basalts and FDS rhyolites are very rare. In general, discriminant models for the origin of sands in different geotectonic environments such as, for example, islands in subduction or continental collision areas (Dickinson 1985; Affolter and Ingersoll 2019), cannot be used in hotspot islands as the percentages of grains of quartz, feldspar or felsic and acidic rocks are low or non-existent (Marsaglia 1993; Le Pera et al. 2020).

The data with respect to calcareous bioclastic grains for the Canary beaches indicate a predominance of both flora and fauna. In some beaches, abundant mollusc fragments are found (N and S of Lanzarote, Corralejo, S of Gran Canaria), and in others, coralline red algae (La Graciosa, Telde, Las Canteras). The latter are common today in subtidal and platform waters in the Canaries (Portillo 2008) and include, for example, *Jania rubens*, *Liagora sp.*, *Haliptilon virgatum*, *Hypnea spinella*, *Halopithys* and *Pterocladia capillacea*. It is, therefore, easy to find algal grains in present-day beach-dune systems and in beachrock and Quaternary eolianites. In Cape Verde beaches, there is a notable predominance of flora over fauna grains (Johnson et al. 2013; Le Pera et al. 2021), whereas in Hawaii, there is a greater abundance of bioclastic grains of foraminifera, followed by molluscs, algae and corals. The coralline grains have high abundance values in the older islands as the coral reefs are more developed in them (Marsaglia 1993). Coral sands have not been reported for either the Canary Islands or Cape Verde. Finally, the oldest islands of Hawaii and Cape Verde have higher bioclast values at the expense of a decrease in lithoclasts. In the Canaries, the bioclast values are not dependent on island age, but rather on geological and geographic aspects and on beach-related processes involving anthropogenic alteration. In this regard, after analyzing for significant differences in the number of bioclasts by beach type using a non-parametric Kruskal–Wallis test for independent samples (Fig. 6), while no differences were found between urban and semi-urban beaches, highly statistically significant differences were found between urban and natural beaches ($p=0.000$) and between semi-urban and natural beaches ($p=0.007$). This could indicate that anthropogenic alteration of the beaches is significantly limiting the production of bioclasts in the subtidal and insular platform area of the urbanized environments, as in the case of the urban and semi-urban beaches as opposed to the natural beaches. In addition, other anthropic



Pairwise comparison of beach types

Sample 1-Sample 2*	Statistic test Kruskal-Wallis	Sig.	Adjusted Sig ^a
2-1	0.159	0.690	1.000
2-3	7.219	0.007	0.022
1-3	26.553	0.000	0.000

Each row tests the null hypothesis that the distributions of Sample 1 and Sample 2 are equal.

Asymptotic significances (two-sided tests) are displayed. The significance level is 0.50.

* 1= Urban beaches; 2=semi-urban beaches; 3= natural beaches

Fig. 6 Differences in bioclast distribution according to beach type (urban, semi-urban and natural)

actions in the intertidal or supratidal zones, such as the periodic cleaning of urban beaches, the transit of vehicles, or the sand replacement tasks on beaches suffering erosion could also be influencing this pattern.

As for the intraclasts, these sand grains have low abundance values in all the Canary samples (< 15%), with the highest found in the beaches of Corralejo, La Graciosa and the C sector of Las Canteras. This could be attributable to the presence of nearby Quaternary substrates of beachrock, eolianites and paleosols. In Cape Verde, moderate values of sparite-cemented intraclasts have been recorded, whereas in the Canaries and Hawaii, they are scarce or non-existent (Marsaglia 1993; Le Pera et al. 2021).

It has been possible to relate the high total values of abundance for volcanoclastic grains in some beaches, along with a decrease in total values of bioclasts, to geomorphological aspects such as the location of beaches at ravine mouths or their proximity to cliffs and ravine slopes (Tables 1, 2) which contribute sediments. This tendency has been observed in the beaches of the S of La Graciosa (samples 4–5), NE of Lanzarote (samples 8–9), S of Las Canteras (samples 33–37), Telde (samples 39–40 and 42), and the N and W of San Bartolomé de Tirajana (samples 44–45, 49–50). In contrast, the beaches where the greatest abundance of bioclasts is observed have no coastal area ravines, cliffs or slopes as,

for example, in the N of La Graciosa, in Lanzarote and in Fuerteventura (Corralejo). The influence of landforms was not considered in the consulted published sand provenance analyses for Cape Verde and Hawaii. The analysis of the petrographic data of volcanic bioclasts, intraclasts and lithoclasts in kilometer-long beaches (as with samples 26–37 in the case of Las Canteras) suggests that coastal dynamics could be acting as a homogenizing factor in terms of types of components and that the small variations are due to the influence of geological and geographic factors. Thus, it was found that there is an increase in intraclasts in the C sector of this beach due to the presence of beachrock, eolianite and paleosol substrates. In contrast, in the S sector, there is a higher presence of volcanic lithoclasts (MR-fr and M-min) as a consequence of sediment contribution from the mouth of La Ballena ravine. These variations in components are observed if different beaches on the same island are compared, as for example with the beaches of La Graciosa, Lanzarote or Fuerteventura. Thus, the high bioclast values of El Reducto (Lanzarote) are due to beach regeneration works with nearby eolian sediments. However, sometimes, there are variations in one or other of the different percentages of the abundance which may be attributable to various reasons. By way of example, in the case of the E coast of Gran Canaria (Telde), it is possible to identify the influence of

longshore drift from N to S beaches with the contribution of felsic grains (FR-fr), whereas there are no outcrops of this type in the littoral of the beaches under study in this area.

Finally, in the beaches of Corralejo (Fuerteventura), it was possible to corroborate the conceptual model of Hernandez-Calvento et al. (2017) of an island-encapsulating beach-dune system for a circum-island route of sandy grains in hotspot-associated volcanic islands involving successive littoral beaches and terrestrial dunes. However, in the other beaches studied in the eastern islands, the petrographic results seem to indicate that, though the beaches may have been interconnected at some point in the past, many currently behave as independent coastal sandy systems disconnected from the rest. In these cases, local factors (geographic and geological) and the degree of anthropogenic alteration are the variables that best explain the differences observed in the petrographic analyses.

In the above paragraphs, we have indicated certain similarities and differences between the petrographic results of sandy beaches of the volcanic archipelagos of Hawaii, Cape Verde and the Canary Islands. Likewise, certain tendencies of similarity and divergence concerning the nature of the sand grains (lithoclasts, bioclasts and intraclasts) and their abundance have been pointed out with respect to beaches of a same archipelago, or a same island, a coastal sector or a specific beach.

Taking the results as a whole, there is a notable high variability in those of petrogenetic character. This is attributable to the different factors that intervene at different spatial and temporal scales. The most noteworthy of these factors are the following: geotectonic (anomaly of the mantle, lithospheric plate and oceanic ridge, hot spot activity, closeness of the continental lithosphere, etc.); geological (island formation stages, petrogenetic, magmatic and sedimentary mechanisms, petrology and texture of the materials, rocky substrates, etc.); geographic (latitude, climatology, land forms, anthropic interventions, global terrestrial changes, etc.); oceanographic (general ocean circulation, currents, local tides and swells, ecosystems, marine productivity, etc.). Consequently, from the petrographic point of view, there will always exist quantitative and qualitative differences which, at a given scale, will endow singularity on each of the beaches.

Conclusions

The review of the petrographic data from 35 beaches in the islands of La Graciosa, Lanzarote, Fuerteventura and Gran Canaria, and their contextualization in their respective geographic and geological environments, has allowed us to determine the nature of the sand grains, their relative

abundance and the variability of their different sources. The main conclusions are as follows:

1. The presence and abundance of volcanoclastic grains on the studied Canary beaches are related to the different volcanic construction stages of the environments where they are situated. Thus, the mafic and ultramafic terrigenous components (rocks and minerals), with porphyritic textures, are associated with the shield construction stage (MSS) of Miocene polygenetic volcanoes, and to the rejuvenation stages (MRS) in Plio-Quaternary monogenetic edifices. In contrast, the trachytic felsic components, with variable alteration, are associated with the Miocene alkaline decline stage (FDS). In both cases, the abundance percentages depend on the proximity of each substrate type to the beach. In some cases, the fragments come from nearby cliffs, while in others they have been transported by ravines.
2. The most abundant calcareous marine bioclast grains are fragments of coralline algae and molluscs, while in contrast, the values of foraminifera, echinoderms and bryozoans are very low. Unlike in Hawaii and Cape Verde, the abundance values of total bioclasts are not dependent on island age but are instead associated with geological and geographic factors and to the degree of anthropogenic alteration of each beach. Thus, the highest bioclast values are observed in the natural beaches and are sharply reduced in urban and semi-urban beaches. For their part, the percentages of the abundance of bioclasts are also lower on beaches close to ravine mouths, cliffs and ravine-associated colluvial slopes.
3. The percentages of intraclast grains are low in the studied beaches, and when appearing are related to the presence in the beach of Pleistocene–Holocene sedimentary substrates (beachrock, eolianites and paleosols).
4. The studies of Canary beaches show high variability in terms of identified component type and in their abundance percentages. Variations are found between beaches of the same island and between islands. This can be attributed to the local diversity that characterizes the Canary Islands, both in terms of geological elements (materials, landforms and structures) and geomorphological and anthropic processes. Most of the beaches studied currently behave as independent sedimentological systems in which natural and local anthropic factors play a major role.

Author contributions The study conception, design, material preparation, data collection, analysis and interpretation were performed by the two authors (Mangas J. and Perez-Chacon Espino, E.). Section 3.1. Geological and geographic characteristics of the beaches under study has been made by E. Perez-Chacón Espino and 3.2. Petrography of the

sands and percentages of abundance of their components by J. Mangas. The other sections have been made by the two authors. Figures 1 and 6, and table 1 have been made by E. Perez-Chacon Espino. Figures 2, 3, 4 and 5, and table 2 have been made by J. Mangas. The first draft of the manuscript was written by the two authors and several versions were made until the final manuscript was reached. The latest version was revised by a native English professional.

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Declarations

Conflict of interest The authors have not disclosed any competing interests.

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