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Physico-chemical alteration of pyroxene in coastal environments: empirical constraints from New Zealand and the Azores

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Abstract

Developing approaches to determine the modes of transport and weathering of mafic detrital minerals in natural sedimentary environments is critical to our understanding of sediment production, dispersal and provenance, as well as carbon capture under natural and enhanced weathering regimes. We integrated the characterization of morphological and surface textures with the surface composition of recent detrital clinopyroxene grains concentrated in a sandy coastal area from the western North Island of New Zealand and a rocky shore area of Santa Maria Island in the Azores Archipelago. Using the compactness shape descriptor, 341 grains were subdivided into elongated, elongated angular, euhedral, angular and subangular groups, with each group further characterized using morphological and microtextural indicators of abrasion, breakage and dissolution/chemical weathering. In both studied environments, the clinopyroxenes are dominated by elongated to angular shapes with flat cleavage surfaces and conchoidal fractures. This is consistent with dominant subaqueous transport by rivers and longshore currents for New Zealand, and dominant wave action with limited sediment supply by rivers along the rocky shore of Santa Maria. More abundant subabraded and abraded shapes with bulbous and elongated depression microtextures are observed in New Zealand, which indicates additional effects by eolian transport that are not seen in Santa Maria. Consistent with semi-quantitative EDS spot analyses that document fresh clinopyroxenes surfaces, chemical weathering textures are very rare to absent. In Santa Maria, sampling of recent beach sand was complemented by ~125 kyr-old palaeobeach clinopyroxenes, but these yielded similar textural results without evidence for chemical weathering. However, the surface of these older clinopyroxenes includes small adhering smectite (typically <50 µm in width and a few µm in thickness) interpreted to reflect incipient cementation with buffering of acidic fluids by more reactive lithic fragments in the deposits. The lack of chemical weathering but pervasive evidence for mechanical breakage of clinopyroxenes indicate that, at the sand size, these minerals break faster than they dissolve due to frequent subaqueous and/or aeolian reworking in the studied high-energy environments and temperate climatic conditions.

Keywords: clinopyroxene, surface textures and composition, beach dune, rocky shore, carbon capture, New Zealand, Azores.

1. Introduction

The shape and microtextures of monomineralic detrital sand grains are physical attributes that reflect fluvial, marine and aeolian transport in the sedimentary cycle (Russell and Taylor, 1937; Kuenen 1959, 1960; Dott, 2003; Mahaney, 2002; Garzanti et al., 2015a; Turner and Morton, 2007). Quantitative measurements of the grain's shape are valuable to investigate source to sink processes. Notable examples include the use of (i) the orthogonal axes of pebbles and gravels (Zingg, 1935; Oakey et al., 2005), (ii) the roundness, form and compactness in sands (Diepenbroek et al., 1992; Zhao and Whang, 2016), (iii) the roundness, angularity, irregularity, fractal dimension, convexity, solidity and rectangularity in sands (Tunwal et al., 2018); the roundness, sphericity and roughness in constructed particles and sands (Mo, 2020), and (iv) the roundness in quartz and heavy minerals (Thomas et al., 1995; Kasper-Zubillaga, 2009; Resentini et al., 2018). Quantitative shape measurements can be complemented by the characterization of microtextures preserved in light (Krinsley and Donahue, 1968; Krinsley and Doornkamp, 1973; Mahaney 2002; Madhavaraju, et al., 2009, Costa et al., 2012; Vos et al., 2014; Itamiya et al., 2019) and heavy minerals (Moral-Cardona et al., 2005; Mejía-Ledezma et al. 2020). Recently, the study of clinopyroxene morphology based on the compactness shape descriptor and microtextures unveiled contrasted physical processes that prevail along a sandy and rocky volcanoclastic coastal areas (Kasper-Zubillaga et al., 2023), where sand grains experience contrasting morphological changes under subaqueous- and wind-induced transport and weathering (Andò et al., 2012; Resentini et al., 2018).

The microtextures of pyroxenes have also been linked to chemical processes during regolith formation, hydrothermal alteration/mineralization, meteorite alteration, and diagenesis (e.g., Turner and Morton, 2007; Velbel, 2007; 2012; Velbel and Barker, 2008; Andò et al., 2012; Phillips-Lander et al., 2017). Together with experimental work these studies show that chemical alteration is commonly associated with the formation of etched pits and denticles, with sometimes evidence for the development of a thin ($0.01 < \text{mm}$ thick) leached silica-rich layer on the surface of the minerals (Bouissonié et al. 2020; Monasterio-Guillot et al. 2021). However, although detrital pyroxenes are common in volcanoclastic deposits on Earth, there are still very few studies that consider both their morphological characteristics to disentangle physical and chemical processes occurring during the transport and deposition of sediments (Velbel, 2007; Velbel and Barker 2008; Kasper-Zubillaga et al., 2023). Sediment provenance studies usually focus on the relative abundance of both monocrystals and polymineralic grains within the sediment routing system (e.g. Allen, 2017) without detailed constraints from mineral morphologies and microtextures on possible physicochemical causes for mineralogical changes. Empirical studies on the dissolution of pyroxenes in natural environments or controlled experimental conditions typically do not directly characterize physical processes (e.g., breakage, comminution, and abrasion) that could occur concurrently with chemical alteration during sediment transport in natural systems. Yet, integration of physical and chemical processes associated with the transport of detrital minerals like pyroxenes is needed to better reconstruct geoenvironmental conditions in sedimentary systems, with applications ranging from fundamental sedimentary research in volcanic environments (e.g., Marsaglia, 1993; Le Pera and Morrone, 2020; Morrone et al., 2021; Kasper-Zubillaga et al., 2023) to determining whether the addition of mafic igneous minerals in coastal environments can help promote carbon dioxide sequestration through enhanced weathering (Renforth and Henderson 2017; Foteinis et al. 2023).

We use here a combined morphological and geochemical study of detrital pyroxenes from two volcanic island settings, which deposited under similar climatic and weathering conditions to constrain possible variables during transport and deposition in sandy to rocky high-energy

coastal environments. Only relatively similar climatic conditions are considered here for better understanding of sand characteristics controlled by contrasted coastal processes (as opposed to contrasted climatic processes).

2. Study areas

2.1 New Zealand North Island

The first study area is located in the western coastal area of New Zealand North Island west of Auckland City (Fig. 1). Average annual precipitation ranges 1000-1500 mm whereas average annual temperatures at sea level ranges from 16 to 12 °C (Norton, 1985). The area includes the Muriwai dissipative beach that is exposed to a high energy swell (Short, 2003), and the Waikato River that is the largest (425 km long) drainage system on the southwestern-central coastline of the North Island. A wave-induced northward longshore drift is reported near the Muriwai beach area based on grain size and mineralogic trends (Hamill and Ballance 1985). Waves are induced by frequent southwesterly onshore winds with average velocities ranging from 5 to 10 m/s (Pickrill & Mitchell 1979; Heath 1982). The New Zealand North Island sandy coastal area has a weathering-limited erosion regime (Johnsson et al., 1993; Dawn et al., 2007; Le Pera et al., 2021; Kasper-Zubillaga et al., 2022).

The western coastal area of the New Zealand North Island is adjacent to the volcanic Waitakere Ranges that includes alkaline basalts to basaltic andesites and primary to secondary volcanoclastic sediments (e.g., tuff, volcanic breccia) (Hayward 1983). The erosion of these rocks provides heavy minerals to the beach and dune sands along the Muriwai coast, including brown hornblende, augite, Ti-magnetite and minor ilmenite (Hamill and Ballance, 1985). An alternative parental source to the composition of the Muriwai beach and dune sands is the Taranaki Volcanic area that is located on the southwestern central area of the New Zealand North Island. That area includes basaltic andesites to andesites that provide olivine, orthopyroxene, clinopyroxene, amphibole, plagioclase, titanomagnetite and ilmenite in the beach sands (Hamill and Ballance, 1985; Price et al., 1999). Transverse vegetated dune systems have developed along the Muriwai beach area extending as a Holocene barrier system (Brander and Short, 2000).

2.2 Santa Maria Island (Azores Archipelago)

The second study area is Santa Maria, the southeasternmost island in the Azores Archipelago (Portugal), which formed in the North Atlantic Ocean as result of hotspot magmatism close to the Mid-Atlantic Ridge (Fig. 2) (Sibrant et al., 2015; Ramalho et al., 2017; Marques et al., 2020). Santa Maria Island is a geomorphologically asymmetric island that culminates at 597 m at Pico Alto. The coastline is typically composed of high steep cliffs, with limited sand/gravel beaches along protected bays such as Praia Formosa or São Lourenço (Ricchi et al., 2020). Mean annual precipitation between 1873 to 2012 is relatively low e.g. 960.6 ± 201 mm with 75% of the total precipitation observed between October and March (Hernandez et al., 2016). The mean annual temperature is 17.5 °C (Borges et al., 2020). As a result, Santa Maria Island is characterized by torrential fluvial erosion regime. High wave energy contributes to erosion and sediment reworking along the coast of the island (Krastel et al., 2001; Ramalho et al., 2017). The Azores Archipelago, including Santa Maria Island, are particularly affected by severe storms with wave heights exceeding 16 m reported at least once every seven years (Andrade et al., 2008; Zhao et al., 2019). Frequent northeasterly and southwesterly wind velocities in one year fluctuate from 5 to 8 m/s (Melo et al., 2020). Like for the New Zealand North Island study area, the Santa Maria Island rocky coastal area is exposed to a weathering-limited erosion regime (Johnsson et al., 1993; Le Pera et al., 2021; Kasper-Zubillaga et al., 2022). Without recent volcanism and large drainage systems, volcanogenic sediment deposited in sand beaches

is predominantly produced through the erosion of coastal cliffs by wave dynamics. Little sand accumulates along the coast due to removal by storms to the inner shelf and offshore environments (Quartau et al., 2012).

Santa Maria Island consists of two overlapping volcanoes separated by a ca. 0.8 Myr long period of dormancy and erosion (Serralheiro et al., 1987; Serralheiro and Madeira, 1993; Ramalho et al., 2017). Basanites and picrobasalts are the dominant igneous rocks of this volcanic system (Larrea et al., 2018). Transgressive to regressive marine quaternary cycles led to the emplacement of foreshore-beach deposits from the Late Pleistocene to Early Holocene in the southern side of Santa Maria Island (Ávila et al., 2018). These palaeobeaches preserve coastal sands emplaced during the Marine Isotope Substage 5e (MIS 5e, ca. 125 ky ago). They were considered here to evaluate longer term alteration of pyroxenes and possible changes in coast dynamics controlling sand transportation.

3. Methods

3.1. Field sampling and sample preparation

Sands from New Zealand North Island were collected from four sites at the foreshore of the beach and the stoss and lee face of the dune at Muriwai. The Santa Maria Island sands were taken from three spots at Formosa beach and three heavy mineral-rich (dark) layers at the MIS 5e palaeobeach next to Prainha beach. In contrast to Muriwai beach samples, Santa Maria sands contain abundant bioclastic grains which did not obstruct the pyroxene grain separation procedure. No chemical solution pretreatment (Krinsley and Donahue, 1968; Lewis and Armstrong, 1995; Helland and Holmes, 1997; Moral-Cardona et al., 2005; Madhavaraju et al., 2009) was used to preserve the original surface texture of the grains. Separation of pyroxene grains was initially performed with a fraction of the sand sample (~0.5 g) placed in a Petri-dish under a binocular microscope objective 4X for hand-picking. Grains were selected based on their noticeable green and dark green color and consist of monocrystalline pyroxenes free from groundmass. Their size ranges from 100 µm to 2 mm, which make them suitable for assessing prevailing surface textures (Vos et al., 2014). The Santa Maria Island palaeobeach pyroxene grains were analyzed separately as unwashed (Un) and washed (W) grains. Unwashed grains come from unrinsed sand samples whereas washed grains were separated after substantial rinsing of the sand samples with running clean water in order to remove salt and clay free particles and compare the EDS geochemical spectra between recent beach and palaeobeach grains, as further explained below. Higher Na EDS bias resulting from thin halite minerals on the surface of some grains was efficiently addressed by this method, as further discussed below. No further ultrasonic vibration protocol to clean the pyroxene grain was employed since surface textures may be damaged (Porter, 1962).

3.2. Geochemical analysis

Data acquisition and geochemical procedures for New Zealand North Island (n = 123) and Santa Maria Island (n = 401) are based on the approach by Kasper- Zubillaga et al. (2023). Crystals were mounted and coated with carbon for energy dispersive spectroscopy (EDS) semi-quantitative analysis and topographic BSE grain morphology/ surface textures imagery using a Zeiss Sigma HD field emission gun SEM equipped with two Oxford Instruments 150 mm² EDS detectors located in the School of Earth Environmental Sciences, Cardiff University, UK. Grains were imaged and analysed using a 15 kV beam energy using a 60 µm diameter final aperture with a beam current of ~1 nA. Some pyroxenes grains were analyzed several times to improve the reliability of the geochemical results and ensure recognition of possible geochemical heterogeneities at the surface of the minerals. For the Santa Maria Island palaeobeach (Un - W) sands, where enhanced discrepancies in the Al₂O₃, CaO, NaO, FeO, MgO contents were detected, EDS spot analyses were typically performed two to six times per

grain to assess geochemical variability. Where several analyses were performed on a single pyroxene grain, relative standard deviation was typically <2% for SiO₂, <20% for TiO₂, <20% for Al₂O₃, <12% for FeO, <8% for MgO and CaO, and <26% for Na₂O, thus indicating that our semiquantitative analyses provide reliable estimates of mineralogical compositions for this study.

3.3. Morphology of pyroxenes

The morphology of the detrital pyroxenes was characterized using three shape parameters: 1) grain size, 2) compactness, and 3) microtextures. These parameters were obtained from (2D) petrographic images using the J Microvision v. 1.3.4 software (n = 399 grains) (Bribiesca, 2000; Roduit, 2007; 2019). Grain size was quantified using the optical diameter of the particles (i.e., diameter of the grains closed to a circle) and was calculated with the formula $D = 2 \sqrt{A/\pi}$. (Appendix 2).

Compactness is defined as the ratio of the area of the object to the size of a circle with the same perimeter:

$$C = 4 \pi A / P^2$$

where C = compactness, A = area of the shape, and P^2 = squared perimeter of any object (Osseman, 1978; Bogaert et al., 2000; Montero and Bribiesca, 2009; Li et al., 2013).

Compactness is an alternative shape descriptor that determines the particle shape and encompasses the enclosing sphere ($4 \pi A$) that contains the particle and its perimeter (P). It is defined by (i) the sphericity of a particle, i.e. the ratio of the surface area of a sphere with the same volume as the given particle to the surface area of the particle (Wadell, 1932), and (ii) the convexity shape defined as the ratio of the volume of a particle to the volume of the convex hull or the smallest polygon drawn from a series of points within an image (Graham and Yao, 1983; Montero and Bribiesca, 2009; Zhao & Whang, 2016). The compactness property is not correlated to the roundness parameter and provides a distinct insight into key morphological characteristics of detrital grains (Kasper-Zubillaga et al., 2023).

Measurements of the compactness and grain sizes (mm) for each grain were determined by the methodology previously reported by Kasper-Zubillaga et al. (2023) and by contouring each grain with single polygon interaction around the image's external silhouette to improve the grain's shape in 2D and preserve the grain's contour as much as possible (Ramer, 1972; Roduit, 2007; Chaudhuri et al., 2012).

Fourteen types of surface textures were quantified by visual inspection and reported as relative abundances normalised to 100% (Appendix 2). Mechanical surface textures produced by water and wind action include conchoidal fractures (CF), arcuate steps (AS), straight steps (SS), meandering ridges (MR), flat cleavage surfaces (FCS), upturned plates (UP), and bulbous edges (BE). Mechanical/chemical or a mix of physically- and chemically- induced surface textures include elongated depressions (ED), adhering particles (AP), and arcuate/circular/ polygonal cracks (ACPC). Surface textures produced by chemical or diagenetic reactions include solution pits (SP), lenticular edge pits (LEP), mamillated textures (MAM), and denticular textures (D) (Krinsley and Donahue, 1968, Krinsley and Doornkamp, 1968; Grandstaff, 1978; Moral-Cardona et al., 2005; Kasper-Zubillaga et al., 2005; Velbel and Ranck 2007; Velbel and Barker, 2008; Vos et al., 2014; Mejia-Ledezma et al., 2020; Madhavaraju et al., 2022; Kasper-Zubillaga et al., 2023).

4. Results

4.1. Geochemical composition

Semi-quantitative SEM EDS analyses of grain surfaces support the occurrence of detrital clinopyroxenes in all studied samples, with well-defined diopside to augite compositions in New Zealand and Santa Maria sands (Appendix 1) (Fig 3 A). Consistent with alkaline and subalkaline magmatism at these two tectonic settings, binary diagrams outline systematic compositional differences in the clinopyroxenes, with notably higher Ti and lower Fe at a given Mg value in Santa Maria pyroxenes (Figs. 3 C, E). Several analyses reveal the occurrence of distinct compositions on the surface of clinopyroxenes from Santa Maria palaeobeach deposits, which are associated with trends departing from typical pyroxene compositions. As further discussed in Section 5, these observations are interpreted to relate to the occurrence of small-sized secondary minerals on the surface of the clinopyroxenes.

4.2. Grain size

Sands from the New Zealand are fine to medium sands ranging from 0.18 to 0.48 mm. In contrast, the Santa Maria Island beach sands are only medium sands ranging from 0.23 to 0.68 mm and the Santa Maria Island palaeobeach sands are medium to coarse sands ranging from 0.23 to 0.99 mm (Fig. 6). Finer sizes are concentrated in beach and dune sands from the New Zealand North Island whereas the coarser sizes are deposited in the Santa Maria unconsolidated palaeobeach outcrops.

4.3 Morphology

Compactness values range from low 0.52 to high 0.96 (Table 1). These values together with the visual inspection of each grain were used to classify the clinopyroxenes into morphological categories to help determine the extent of breakage and/or abrasion effects.

Seven morphological types were identified and characterized as elongated or large grains with negligible sharp edges outlines, elongated angular or large grains with angular-pointed outlines, euhedral or relatively pristine crystals, angular or small grain with angular-pointed outlines, subangular or small grain with less angular-pointed developed features, sub abraded or grains with some smooth attrition and abraded or grains with smooth outlines. The first five shape morphologies have compactness values between ~ 0.51 to 0.78 for 60 % of the grains whereas the subabraded and abraded forms have compactness values between ~ 0.78 to 0.90 for 30 % and ~ 0.90 to 0.96 for 10 % of the grains respectively (Table 1; Figs. 4, 7 A - G).

A confusion matrix was obtained using a linear discriminant analysis (see Ebengo et al., 2021) for all clinopyroxene morphological groups and their corresponding compactness value (Appendix 2). The best classified types yielded an accuracy of 70%, 52%, 67% and 64% for clinopyroxene shapes from the New Zealand North Island, Santa Maria beach, and Santa Maria palaeobeach sites, respectively, and 56% for all clinopyroxene grain's shapes irrespective of their provenance (Table 2). Noticeably, the best clinopyroxene grain's shapes classification within their same corresponding group is for the subabraded and abraded morphological types as observed for groups F and G (see Table 2). These shapes tend to exhibit more regular "polygon shape types" that persistently may lead to compactness values ≥ 0.80 (Rosenfeld, 1973; Kasper-Zubillaga et al., 2023). Hence a thorough visual inspection of each grain is recommended to assign the grain's shape within a specific group based on the compactness descriptor, even though this exercise may be associated with minor subjective biases.

Finally, a correlation between the grain size and corresponding compactness value for each clinopyroxene was determined to highlight the effect of the mineral's size on its morphology ($R^2 = 0.003$; $n = 341$; Fig. 6)

4.4 Surface microtextures

Higher percentages of mechanical microtextures compared to mechanical/chemical and chemical microtextures were observed. Flat cleavage surfaces accounted for the best preserved mechanical surface features for New Zealand samples (34%), Santa Maria beach sands (35%) and the Santa Maria palaeobeach sands (Un: 42%, W: 29%). The rest of the mechanical textures became less pronounced in terms of survivability. For instance, bulbous edges accounted for 17%, 6%, 3% and 13% for the New Zealand North Island, Santa Maria Island beach and Santa Maria Island palaeobeach (Un -W) clinopyroxenes, respectively, whereas conchoidal fractures ($\leq 14\%$ max), meandering ridges (1% max), upturned plates ($\leq 14\%$ max), straight ($\leq 4\%$ max) and arcuate steps ($\leq 10\%$ max) exhibited less abundancies for the three sites (Figs. 8 A – F). The clinopyroxene from the Santa Maria palaeobeach (Un - W) have higher percentages of mechanical/chemical microtextures in the form of adhering particles (39%, 30 %), whereas elongated depressions were more conspicuous in clinopyroxenes from the New Zealand site (12 %) only (Figs. 8 D, E).

The chemical microtextures were almost inexistent and limited to mamillated (New Zealand; 2 % max), denticulated (Santa Maria beach; 1% max) and lenticular edge pits (New Zealand; 8 % max) (Figs. 8 G – J).

5. Discussion

5.1. Clinopyroxene compositions and smectite coating

The clinopyroxenes from New Zealand have augite to diopside compositions with TiO_2 estimates ranging typically between 0.2 and 1.1 wt% (median of 0.6 wt%, $n=123$) (Fig. 3). These compositions can represent mixed subalkaline to alkaline sources (Leterrier et al., 1981). Provenance from the Waitakere Ranges and Mount Taranaki is inferred based on previous sand petrographic studies (Yock, 1973; Hamill and Ballance, 1985). The clinopyroxenes from recent Santa Maria Island sands have augite to diopside compositions with higher TiO_2 estimates of 0.5 to 1.9 wt% (median of 0.8 wt%, $n=82$). These higher values and other major elements (e.g., Al content, Fig. 3B) are consistent with derivation from alkaline igneous rocks of the Anjos and Pico Alto volcanic complexes that border our sampling sites (Forbes and Starmer, 1974; Larrea et al., 2018; Ricchi et al., 2020). In contrast to modern beach sands, the surface analysis of clinopyroxenes from Santa Maria Island palaeobeach defines a broad compositional trend in most major elements (Figs 3 B – F). This trend extends between Santa Maria Island modern beach clinopyroxene compositions and a non-pyroxene endmember with lower Mg and Ca as well as higher Al and Fe contents. Higher Na values are also documented in some palaeobeach pyroxenes (Fig 3 F). The lower Mg compositional endmember associated with palaeobeach clinopyroxenes locally correlates to the occurrence of thin platy minerals on the surface of the grains (typically $< 50\ \mu\text{m}$ in extent) (Figs 3 B - F). These minerals have a consistent smectite composition of ca. $\text{SiO}_2 = 52\ \text{wt\%}$, $\text{TiO}_2 = 1\ \text{wt\%}$, $\text{Al}_2\text{O}_3 = 25\ \text{wt\%}$, $\text{FeO} = 12\ \text{wt\%}$, $\text{MgO} = 4\ \text{wt\%}$, $\text{CaO} = 3\ \text{wt\%}$, $\text{Na}_2\text{O} = 1\ \text{wt\%}$ and $\text{K}_2\text{O} = 1\ \text{wt\%}$ (estimate based on 6 grains recognised by SEM imaging) (Appendix 1). The compositional trend observed in palaeobeach clinopyroxenes is therefore interpreted as an effect of thin smectites on the surface of the clinopyroxenes, which are only rarely seen at the scale of our imaging but are abundant and not removed by washing. Other rarer phases were also observed on the surface of the palaeobeach clinopyroxenes, including calcite and Fe-Ti oxides. In contrast, geochemical analyses of the

surface of clinopyroxenes from the New Zealand North Island and Santa Maria Island modern beaches do not support the occurrence of cryptic minerals on their surface.

Small smectites on the surface of clinopyroxenes in the Santa Maria Island palaeobeach deposits of Santa Maria do not correlate with changes of microtextures in our BSE observations. As further discussed below, there is in fact no or little evidence for chemical alteration of the studied pyroxenes, and therefore the smectites cannot represent an alteration product of the clinopyroxenes (e.g., Noack et al., 1993; Velbel and Barker, 2008). Instead, we suggest that the smectite is incipient cement developing during the early diagenesis or pedogenesis of the poorly consolidated palaeobeach deposits. Albeit palaeobeach deposits are capped by modern soil and crosscut by rare roots from the recent vegetation, they do not include evidence for palaeosol development, which is consistent with limited apparent pedogenic effects in the studied samples. The scale of our SEM images does not allow to precisely determine if the clay orientation in the smectite coatings is tangential or perpendicular to the surface of the pyroxene grains. It remains therefore unclear if the smectites formed in situ due to fluid-pyroxene interaction or were mechanically infiltrated. The ~125 kyr-old palaeobeach deposits include abundant altered glassy volcanic lithics, which we suggest could be the source of the smectite. These grains and carbonate bioclasts could have also played a role in buffering the composition of meteoric water percolating through the sand, hence preventing pyroxene dissolution/alteration. The absence of smectite in the studied active beach environments suggests that frequent sand reworking in subaqueous marine or aeolian conditions does not allow the formation and/or preservation of clay cement.

5.2 Transport and mechanical processes from clinopyroxene morphologies

The clinopyroxene grain morphology (shapes and microtextures) documents distinct transport and mechanical processes in sandy to rocky coastal areas of New Zealand North Island and Santa Maria Island. In New Zealand, elongated, elongated angular, euhedral and angular shapes similar to those observed in coastal volcanoclastic sands from Mexico (Kasper- Zubillaga et al., 2023) are common (Table 1; Figs 9 A – E). This supports rapid fluvial transport to, and long-shore transport along, Muriwai beach with heavy mineral supply from the Waikato River, as also previously suggested by petrographic analysis of the sand (Hamill and Ballance, 1985). Shapes such as those of New Zealand clinopyroxenes are commonly produced by subaqueous breakage during short fluvial transport of quartz (Vos et al., 2004; Mejía-Ledesma et al., 2020), ilmenite (Mejía-Ledesma et al., 2020), tourmaline, rutile, zircon and garnet (Moral-Cardona et al., 2005; Tangari et al., 2021). In addition, mechanical microtextures of New Zealand clinopyroxenes include abundant flat cleavage surfaces (Fig. 5) that are typically produced during high energy fluvial and marine transport (Kasper-Zubillaga et al., 2023). Conchoidal fractures, meandering ridges, upturned plates, straight and arcuate steps are other microtextures that form during high energy subaqueous transport, which are commonly observed in the New Zealand clinopyroxenes (Figs. 5, 8 A, B, C, D, F). In addition to high-energy subaqueous transport, a long-term aeolian influence is required to explain subabraded to abraded morphologies of some of the New Zealand clinopyroxenes, as well as the relatively higher fraction (~18%) of grains with compactness values ≥ 0.87 compared to Santa Maria Island (Figs. 4, 9 F - H). Subabraded and abraded clinopyroxenes preferentially occur after long aeolian action because wind is the most effective agent to grind minerals (Kuenen, 1960; Johnsson et al., 1993; Le Pera et al., 2021; Kasper- Zubillaga et al., 2022), especially in sandy coastal areas with limited erosion. Notable environments where this is well documented include the Namibia coast, western Africa (Garzanti et al., 2012, 2015 a), the Gaza beach, Palestine (Garzanti et al., 2015 b), the western coast of the Gulf of Mexico (Kasper-Zubillaga et al., 2023) and the coast of Southern Italy (e.g., Borrelli et al., 2021). Eolian transport of New Zealand clinopyroxenes is further supported by the occurrence of bulbous edges (Fig. 8 E) that are a typical microtextural indicator of eolian transport for quartz (Kransley & Donahue, 1968;

Kuenen, 1960; Mahaney, 2002; Immonen, 2013; Vos et al., 2014) and ilmenite (Makvandi et al., 2015; Mejía-Ledeza et al., 2020). A record of eolian effects in some of the New Zealand clinopyroxenes is additionally consistent with their occurrence at an extended sandy beach, where wind action is expected to be more effective than at sandy beaches confined within rocky coastal bays such as at Santa Maria Island.

In contrast to New Zealand North Island coastal sands, Santa Maria Island beach sands are thought to be primarily generated by wave- and storm-induced erosion of cliffs with negligible influence of rivers (Quartau et al., 2012). This agrees well with our results that show that the shape of Santa Maria clinopyroxenes are dominated by elongated, elongated angular, euhedral, angular, and subangular morphologies, with few subabraded to abraded grains (Tables 1, 2; Figs 10 A - H). Elongated and euhedral grain morphologies likely result from high energy transport and efficient breakage on the island shelf because clinopyroxenes are prone to split apart along their cleavage surfaces, hence maintaining more angular forms, during prolonged transport by energetic fluvial, littoral drift and/or wave action (Andò et al., 2012; Kasper-Zubillaga et al., 2023). Angular and subangular shapes together with the occurrence of ~60% of the grains with compactness values ≤ 80 (Fig. 4) can be explained by the combination of high energetic waves in the south of Santa Maria Island and frequent storms in the Azores Archipelago (Costa et al., 2012; Quartau et al., 2012; Ávila et al., 2020). Angular morphologies could also relate to recent erosion from the coastal cliffs with minimal subsequent grain abrasion and reworking, as has notably been suggested for beach sands of Lipari Island (Morrone et al., 2018; 2021), but which contrasts with significant abrasion after extensive wind transport as notably observed in clinopyroxenes from the aeolian Namib sands, Africa (Garzanti et al., 2012). Consistent with their shapes, the microtextures of Santa Maria Island clinopyroxenes are dominated by flat cleavage surfaces, conchoidal fractures, meandering ridges, upturned plates, straight and arcuate steps that typically form during high energy subaqueous transport. Conchoidal fractures such as those observed in Santa Maria clinopyroxenes (Fig 8 C) largely reflect the potential action of high energetic waves. Grains collisions occurring under subaqueous conditions produce large conchoidal fractures (100 ~ 250 μm) in poorly sorted sands (Vos et al., 2014). Conchoidal fractures produced by high energetic subaqueous action are also common in minerals like quartz (Kasper-Zubillaga et al., 2005; Reddad et al., 2016; Varghese et al., 2016; Madhavaraju et al., 2022), ilmenite (Mejía-Ledeza et al., 2020), garnet, zircon, tourmaline and rutile (Moral-Cardona et al., 2005), and have also been observed in detrital clinopyroxenes from volcanoclastic coastal environments (Kasper-Zubillaga et al., 2023). Despite the fact that aeolian processes may be significant in Santa Maria Island weather conditions (Andrade et al., 2008; Quartau et al., 2012; Rusu and Guedes Soares, 2012), the minimal abrasion of the studied clinopyroxenes suggests limited aeolian transport (e.g., Garzanti et al., 2012), consistent with the large abundance of subaqueous transport microtextures in the studied clinopyroxenes.

Similar to Santa Maria beach clinopyroxenes, the shapes of Santa Maria palaeobeach clinopyroxenes (washed and unwashed samples) classify as elongated, elongated angular, euhedral, angular, subangular, subabraded and abraded, which are also consistent with prominent breakage by high energy subaqueous transport (Figs 11, 12 A – H; Tables 1, 2). However, Santa Maria Island palaeobeach clinopyroxenes are slightly more abraded than their counterparts from modern beach sands, with 30 % and 12 % of the unwashed and washed grains having compactness values ≥ 0.80 , respectively (Figs. 4, 10 - 12). As documented in New Zealand North Island, more abraded shapes broadly correlate with more abundant bulbous microtextures. These observations suggest more significant wind transport (albeit still minor compared to subaqueous transport) in shoreface to foreshore environments on the southernmost areas of Santa Maria Island during and/or before deposition of the palaeobeach deposits ~125 ky ago (Ávila et al. 2015, 2018).

Microtextures at the three sampling sites include abundant flat cleavage surfaces that are typically produced during high energy fluvial and marine transport (Kasper-Zubillaga et al.,

2023). Differences in the ratio of subaqueous to aeolian microtextural indicators in New Zealand and Santa Maria clinopyroxenes is an important outcome of our study that suggests that prominent breakage due to wave action is an intrinsic characteristic of rocky shore environments, which might be less significant or obscured by wind-related grain shapes and microtextures at sandy coastal environments, where eolian transportation is comparatively more efficient. Remarkably, the lack of significant correlation between compactness and grain size at our 3 sampling sites (Fig. 6) suggests that breakage of the clinopyroxenes along their cleavages could be independent from their scale in distinct coastal environments. These observations imply that clinopyroxenes comminution through cleavage splitting is efficient in coastal volcanic settings. Further constraints on the dynamics of breakage are provided below using morphological indicators of chemical alteration.

5.3 Dynamics of physico-chemical alteration

Mechanical and chemical microtextures in detrital clinopyroxenes are produced by the interaction of physical and chemical processes during sedimentary transport and periods of relative stillness after depositional episodes (Wilson, 2004; Velbel, 1993, 2007; Morton and Hallsworth, 2007). More abundant mechanical/chemical surface textures like elongated depressions developed in the clinopyroxenes from New Zealand North Island compared to Santa Maria sites (Fig. 5), which is consistent with longer wind transport of these grains as documented above. Critically, sparse mamillated, solution pits, and lenticular edge pits surface textures indicate no or very limited chemical alteration in these pyroxenes. Similarly, rare mamillated, denticular and lenticular edge pits surface textures support limited, or an absence of, chemical alteration in the beach and palaeobeach clinopyroxenes from Santa Maria Island. This clearly suggests that subaqueous or early pedogenetic weathering of the clinopyroxenes was inexistent or negligible in the studied environments, in contrast to common observations from weathering studies (Grandstaff, 1978; Velbel, 2007; Velbel and Baker, 2008; Velbel and Ranck, 2008; Phillips-Lander et al., 2017; Tangari et al., 2021) and more particularly observations in andosols (central-southern Italy) (Violante and Wilson, 1983) and saprolitized clinopyroxenites (Ivory Coast, Africa) (Velbel and Barker, 2008). This can be partly explained by high energy subaqueous transport of the sand and fast paced clinopyroxene breakage, as documented above by dominant grain morphologies and surface textures. Negligible presence of adhering particles in the New Zealand North Island and Santa Maria Island clinopyroxenes is also consistent with mechanical alteration during active mobility of the grains (Mahaney, 2002; Immonen, 2013; Vos et al., 2014; Mejía-Ledeza et al., 2020; Baek and Jo, 2023). Therefore, efficient breakage and abrasion associated with frequent reworking in beach environments likely led to comminution of the clinopyroxenes at a rate faster than that required to develop and preserve chemical weathering textures. In other words, *at the sand scale*, clinopyroxenes apparently abrade and/or break faster than they can dissolve/chemically weather.

Interestingly, chemical weathering textures are similarly rare in palaeobeach and modern sand samples of Santa Maria Island (Figs. 5, 8 G - J) (Appendix 2), indicating that, even after > ~125 kyr of burial in poorly cemented, porous supratidal beach deposits, sand-sized clinopyroxenes have not undergone significant dissolution/chemical alteration. This is most likely related to chemical buffering by weathering of volcanic particles such as glass-rich volcanic rock fragments and olivine, which are known to be one to several orders of magnitude more reactive than pyroxenes in experimental aqueous conditions (Heřmanská et al., 2022). Such experimental data are consistent with common alteration of glassy lithic fragments observed in the sand of volcanic islands (Marsaglia, 1993; Le Perra and Morrone, 2020; Morrone et al., 2018, 2020, 2021). Fine particles attaching to the surface of the studied grains includes smectite that probably precipitated from aqueous solution after final sand deposition (McKinley et al., 2002). In the studied sedimentary environments, clinopyroxene survival generally suggests

stable chemical conditions. Clinopyroxene dissolution experiments in a range of pH and temperature conditions do not simply translate to changes of CO₂ concentration in aqueous solutions (e.g., Casey and Cheney, 1993; Knauss et al., 1993). Therefore, limited chemical weathering of sand-sized clinopyroxenes in modern and ancient beach deposits as documented in this study using combined textural and chemical analysis of mineral surfaces further questions their geoenvironmental significance. Although it is in theory an important group of silicate minerals for CO₂ atmospheric uptake, its use in enhanced coastal weathering seems limited, unless more efficient chemical weathering takes place at grain sizes smaller than sand to approach dissolution rates seen in olivine (Heřmanská et al., 2022; Foteinis et al., 2023).

6. Conclusion

Detrital clinopyroxenes from New Zealand North Island and Santa Maria Island sandy and rocky shore environments can be classified as elongated, elongated angular, euhedral, angular and subangular using the compactness shape descriptor, with an overall low abundance of subabraded and abraded minerals. The occurrence of euhedral grains and breakage along mineral cleavages supports fluvial input and longshore drifts for pyroxenes of the New Zealand sandy coastal area. Subsequent effects by wind transport are important, with compactness values ≥ 0.87 , subabraded and abraded shapes in $\sim 18\%$ of the grains, and frequent bulbous edge and elongated depression microtextures. Conversely, euhedral and elongated crystals devoid of significant edge abrasion, bulbous edges, and elongated depressions indicate that clinopyroxene grain shapes in the Santa Maria beach and palaeobeach sites are probably only influenced by wave action. This is consistent with the hypothesis that cliff erosion is the dominant source of volcanoclastic sand-sized sediment in this confined rocky coastal environment, with clastic material not stored very long on the island shelf due to removal offshore by storms and possibly longshore currents. Clinopyroxenes with flat cleavage surfaces and conchoidal fractures are abundant in the high energy volcanoclastic coastal environments of New Zealand and Santa Maria islands, supporting efficient breakage during subaqueous transport. Smaller particles adhering to the detrital pyroxenes were only encountered in palaeobeach deposits of Santa Maria Island, which suggests that they represent early diagenetic (or possibly pedologic) minerals. Small smectite typically $< 50\ \mu\text{m}$ in extent and only a few μm thick are common on the surface of the palaeobeach clinopyroxenes, but these minerals are not associated with dissolution features (e.g., etched pits and denticulated edges), hence suggesting that the smectite represents an early cement. Sparse chemical surface textures in the clinopyroxenes from the New Zealand and Santa Maria beach and palaeobeach sands do not support chemical weathering. We therefore conclude that sand-sized detrital clinopyroxenes break faster than they are chemically altered in the studied high energy coastal environments. Extending observations to smaller grain sizes is required to test whether there is a size threshold at which chemical weathering becomes more efficient relative to mechanical breakage to be recorded on the surface of the grains for carbon capture under natural and enhanced weathering regimes. This study is a first attempt to deconvolute the effects of physical and chemical weathering of pyroxene sand grains in natural environments. Future research could include a comparison of variously reactive mafic minerals in distinct environments covering a broader range of climatic regimes and transport dynamics.

Author's contribution

Juan J. Kasper-Zubillaga, conceptualization, visualization, funding acquisition, writing, editing; David M. Buchs, visualization, methodology, writing, editing, review; Duncan Muir, imagery data curator and EDS analyses; Lizeth Carlos Delgado, map drawing and editing; Elsa Arellano-Torres editing, review; León Felipe Álvarez-Sánchez online repository curator and map contribution.

Conflict of interest

The authors declare that they do not have competing financial interest nor conflict of interest.

Acknowledgments

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FIGURES, TABLES AND REFERENCES ARE PROVIDED BELOW

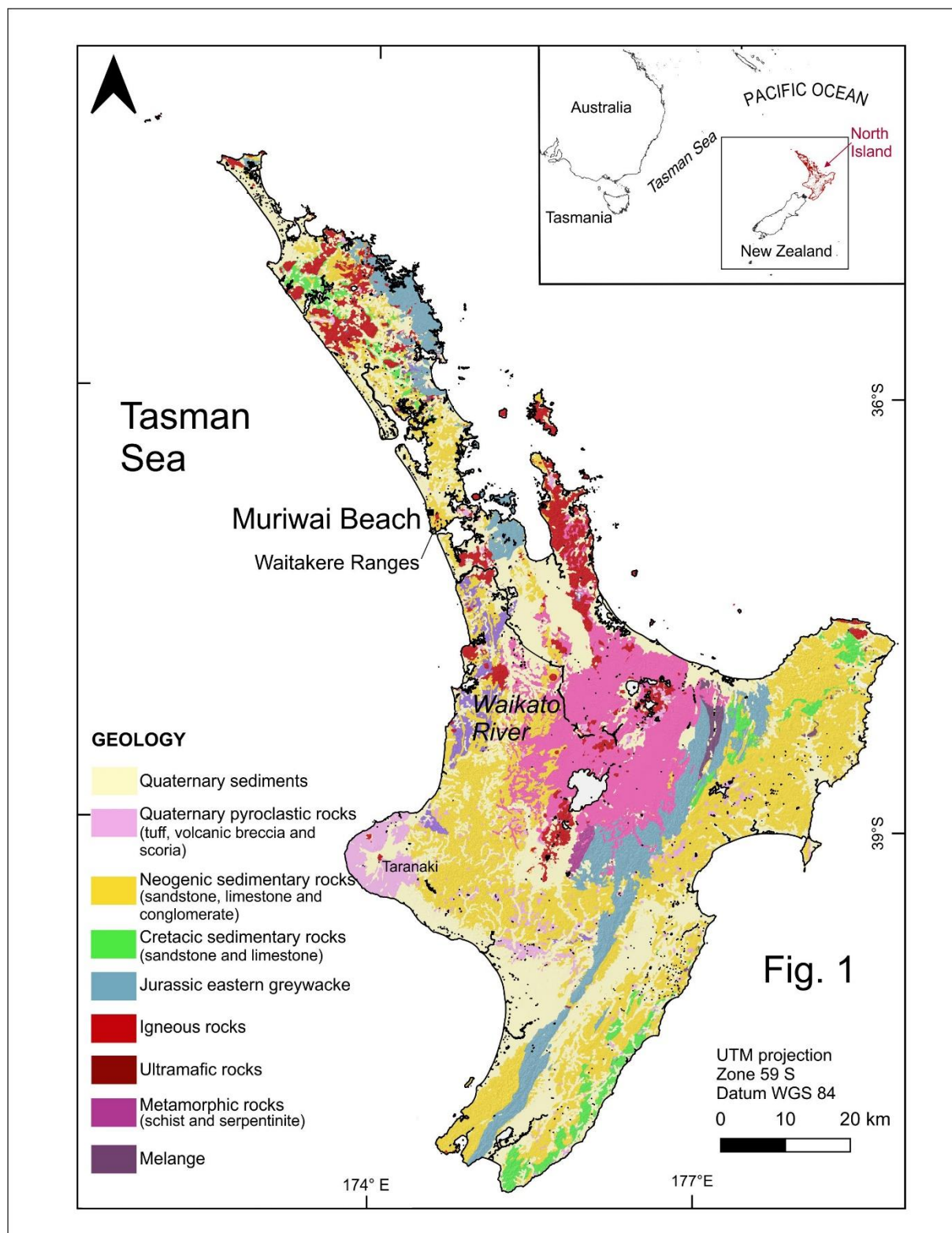


Figure 1. New Zealand North Island. Geology map and location of beach – dune sand samples (Muriwai Beach) (modified from Rattenbury and Isaac, 2012).

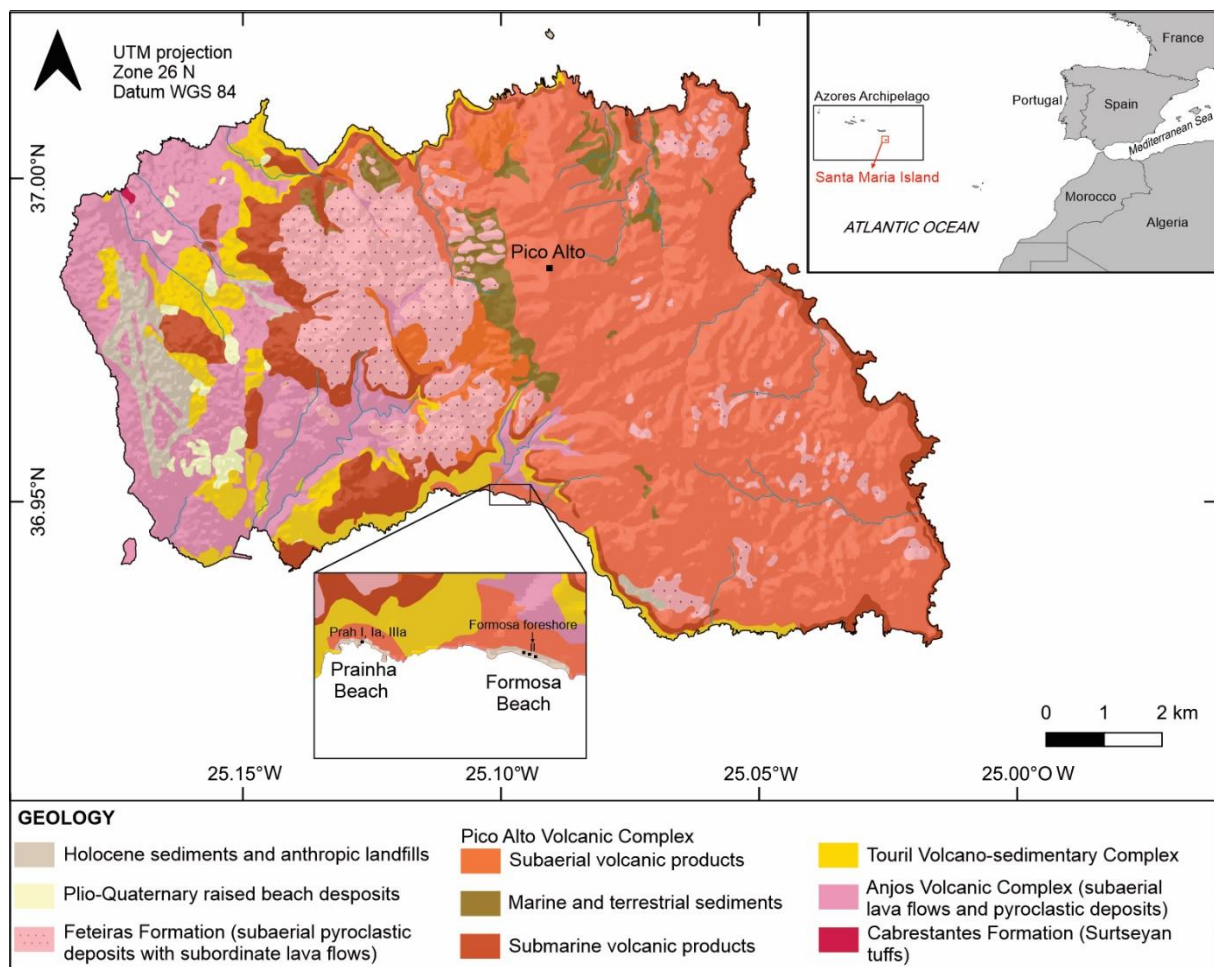


Figure 2. Santa Maria Island geological map and location of beach sand samples (Praia and Formosa Beach) (modified from Ramalho et al., 2017).

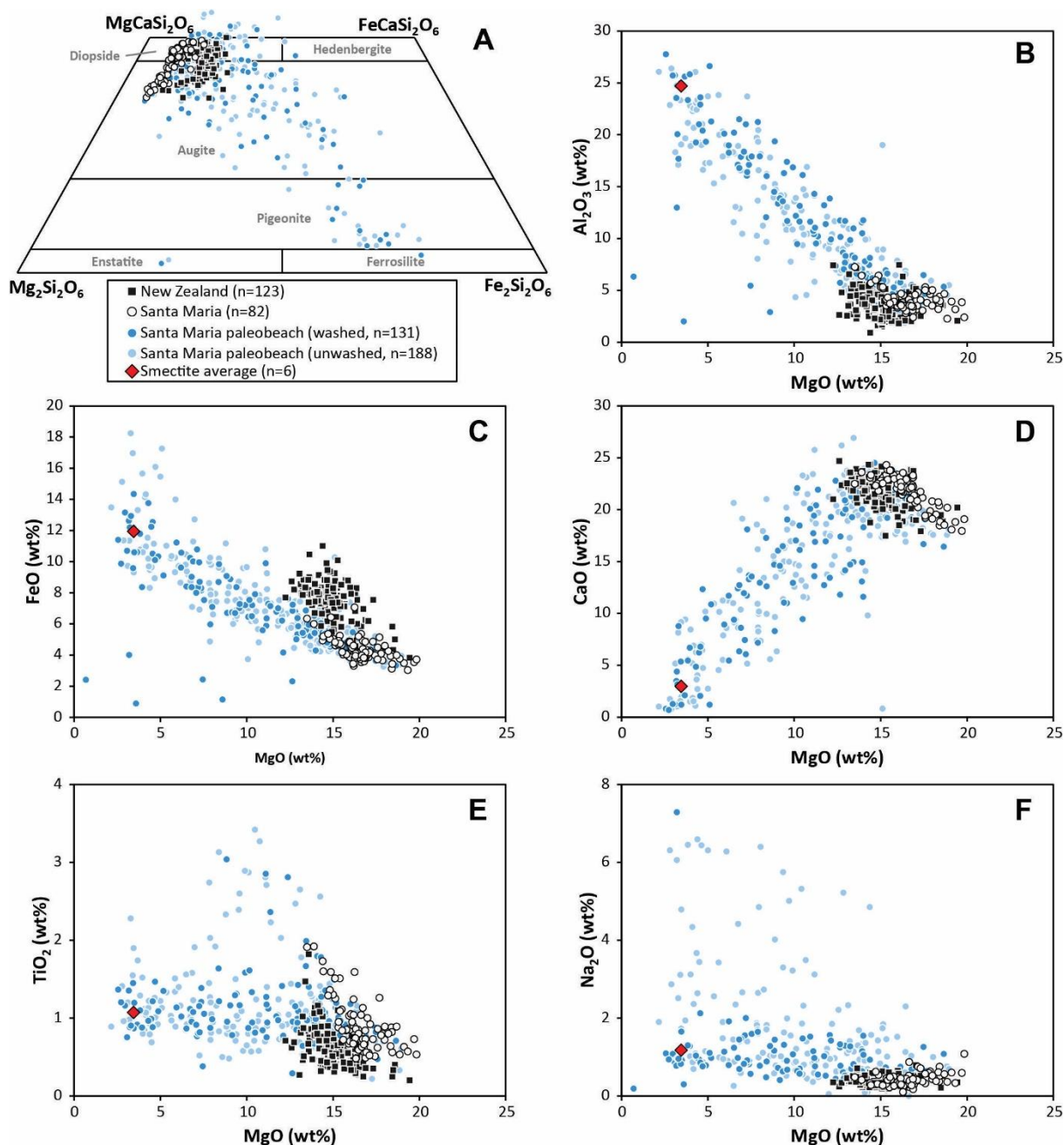


Figure 3. Semi-quantitative EDS SEM geochemical results. (A) Pyroxene classification quadrilateral. The structural formula of the pyroxenes was calculated according to Morimoto et al. (1988). (B - F) Selected major element binary diagrams.

- Grains with elongated, elongated angular, euhedral, angular, subangular shapes
- Grains with subabraded and abraded shapes
- New Zealand beach and dune sands n = 126
- Santa Maria beach sands (Azores Archipelago) n = 88
- Santa Maria paleobeach unwashed (Azores Archipelago) n = 79
- Santa Maria paleobeach washed (Azores Archipelago) n = 48

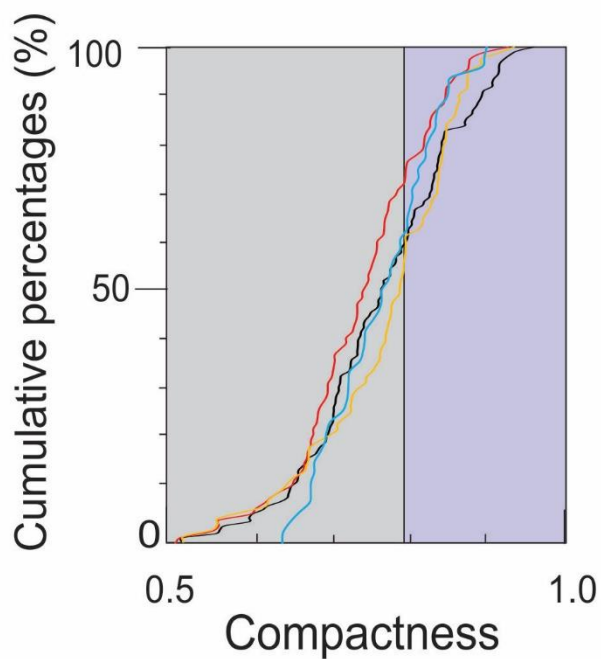


Figure 4. Cumulative plots of C measurements of clinopyroxene grains for the four sites.

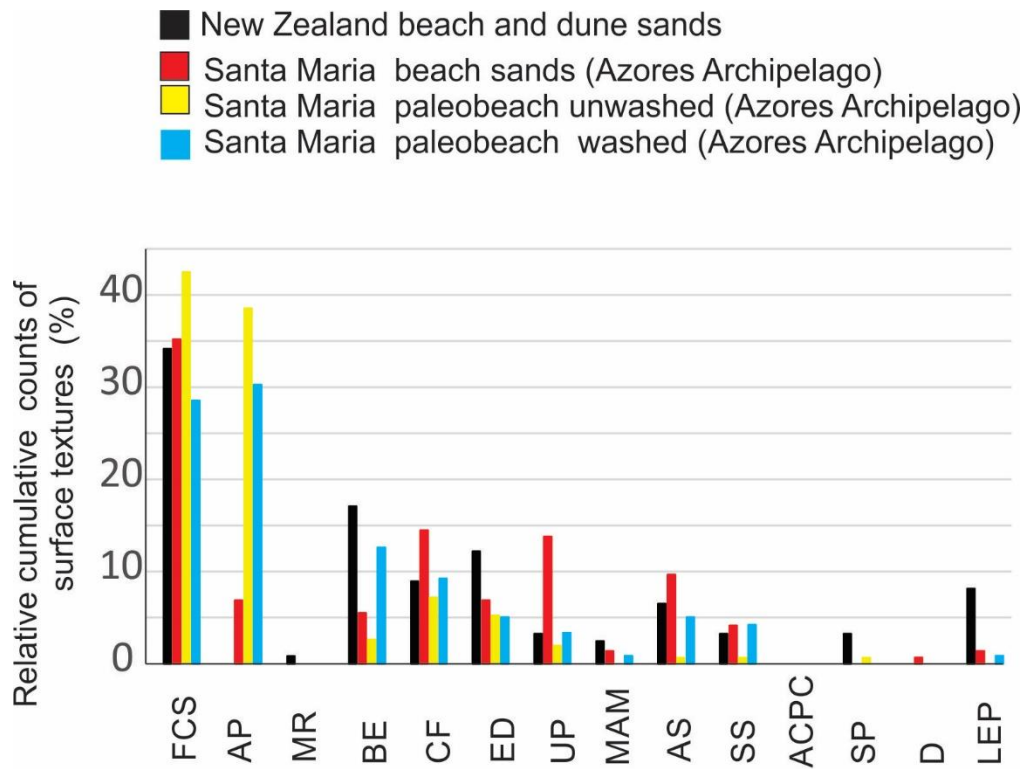


Figure 5. Cumulative plot of surface textures of clinopyroxene grains from the New Zealand North Island, Santa Maria Island beach and paleobeach.

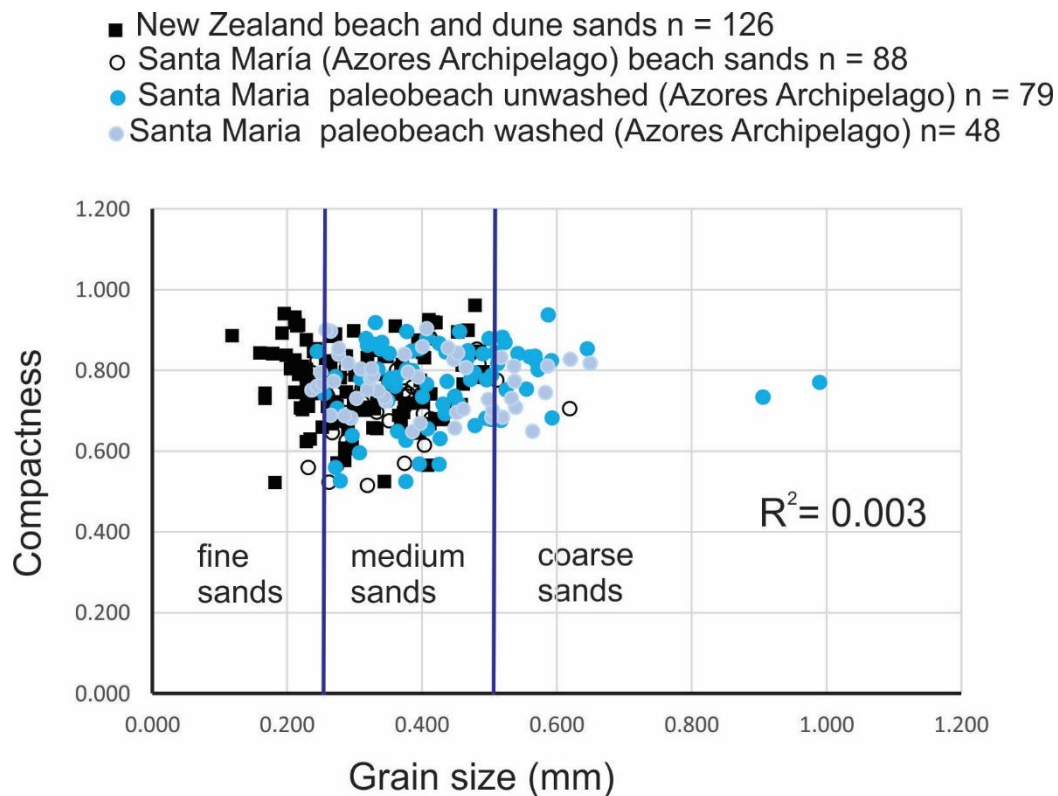


Figure 6. Correlation between compactness and grain size (mm).

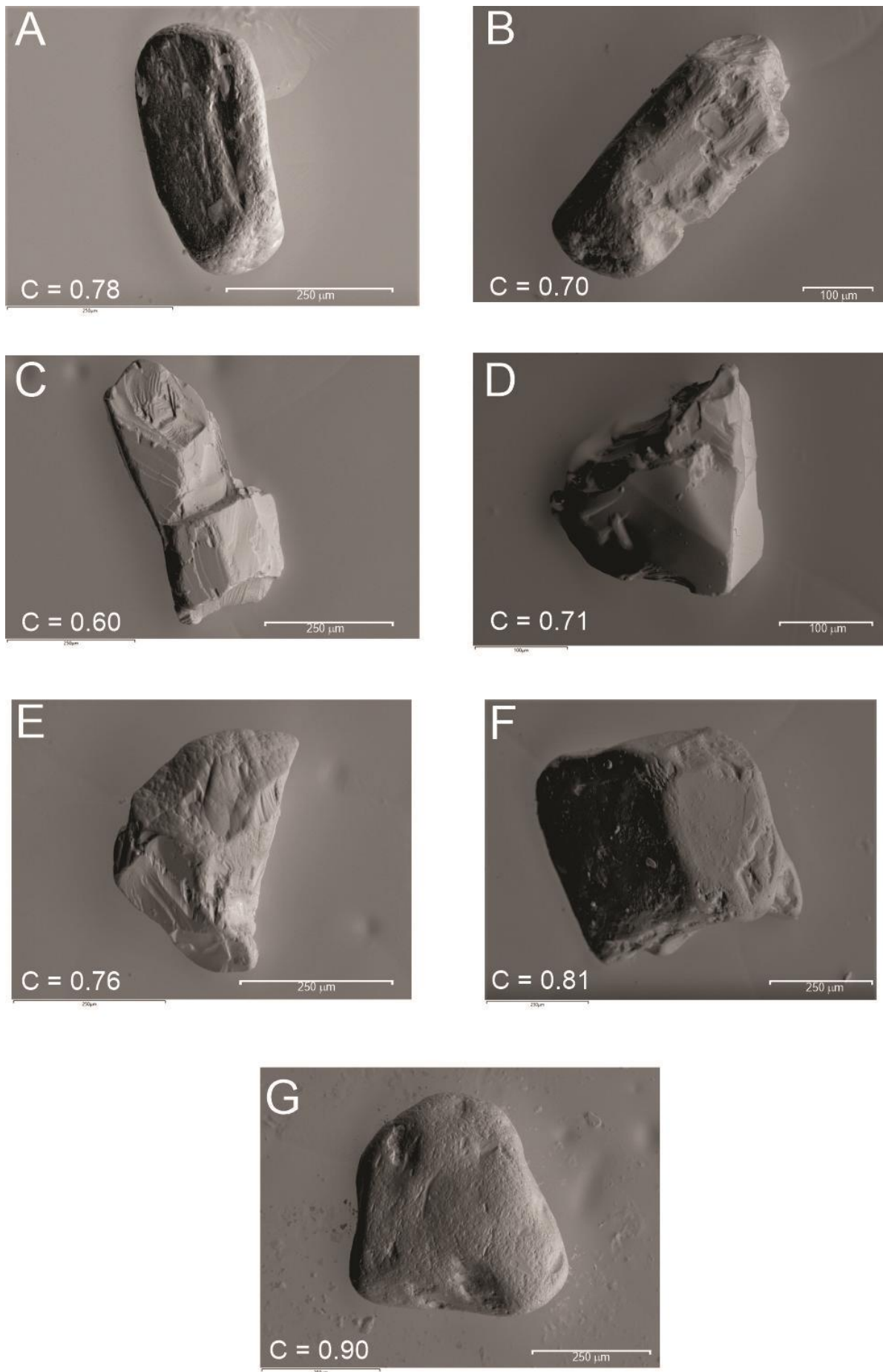


Figure 7. Contrasting compactness values and corresponding clinopyroxene grain shapes: A) elongated or large grains with negligible angular-pointed outlines $C = 0.78$ New Zealand North

Island leeface; B) elongated angular or large grains with angular-pointed outlines $C = 0.70$ New Zealand North Island leeface; C) euhedral or relatively pristine crystals euhedral $C = 0.60$ Santa Maria Island beach Praia 1; D) angular or small grain with angular-pointed outlines $C = 0.71$ New Zealand North Island foreshore; E) subangular or small grain with less angular-pointed developed features $C = 0.76$ Santa Maria Island beach Formosa; F) subrounded $C = 0.81$ Santa Maria Island paleobeach (W); G) rounded $C = 0.90$ New Zealand North Island foreshore.

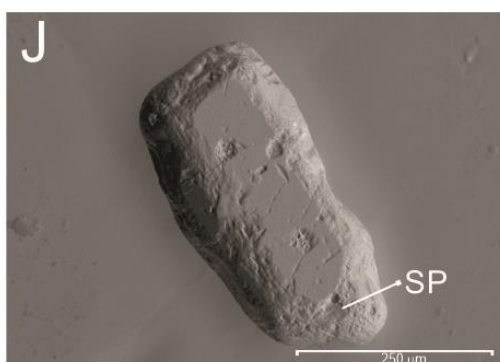
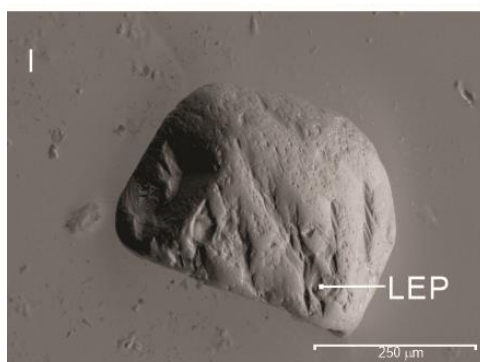
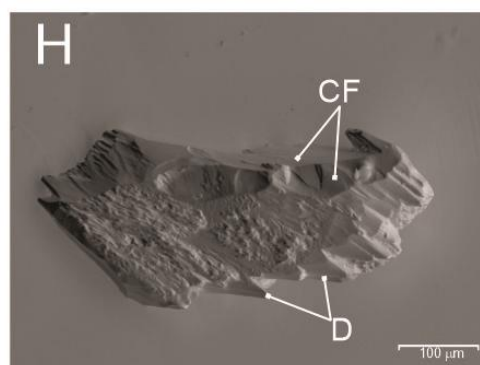
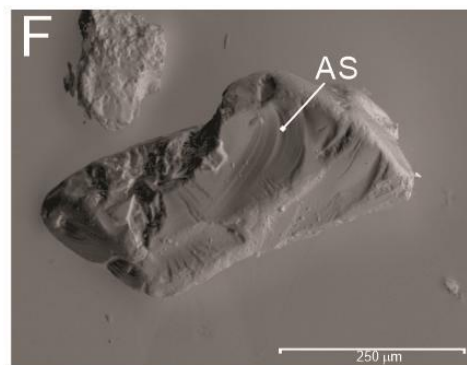
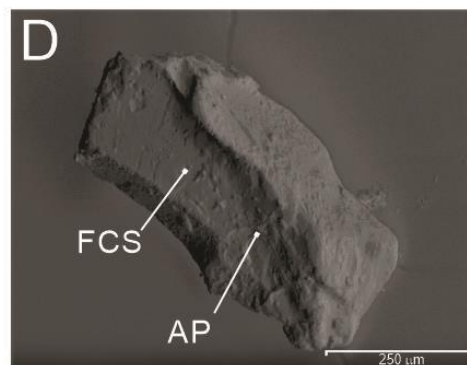
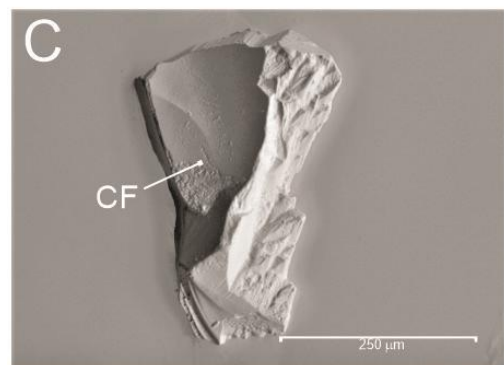
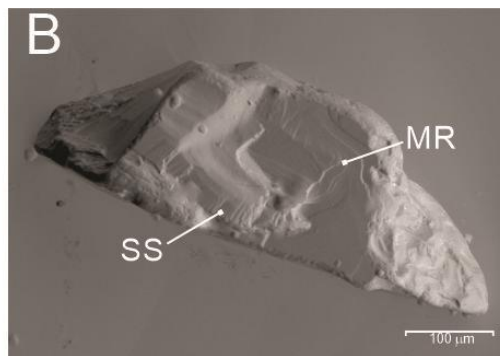
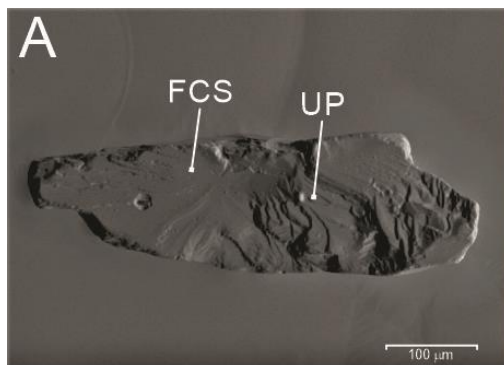


Figure 8 (previous page). Surface textures on clinopyroxene. A) site New Zealand North Island foreshore, B) site Santa Maria Island II foreshore, C) site Santa Maria Island Formosa foreshore, D) site Santa Maria Island paleobeach, E) site New Zealand North Island foreshore, F) site Santa Maria Island Formosa foreshore, G) site Santa Maria Island1 foreshore H) site Santa Maria Island1 foreshore, I) site New Zealand North Island foreshore, J) site New Zealand North Island stoss. FCS = flat cleavage surfaces; UP = upturned plates; SS = straight steps; MR = meandering ridges; CF = conchoidal fractures; AP = adhering particles; ED= elongated depressions; BE =bulbous edges; AS= arcuate steps; MAM =mamillated textures; D = denticular textures, LEP = lenticular edge pits; SP = solution pits.

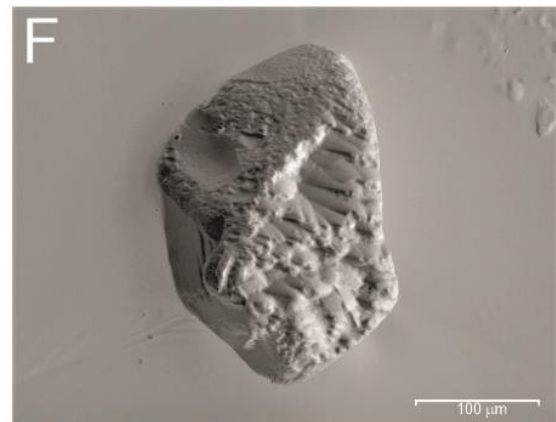
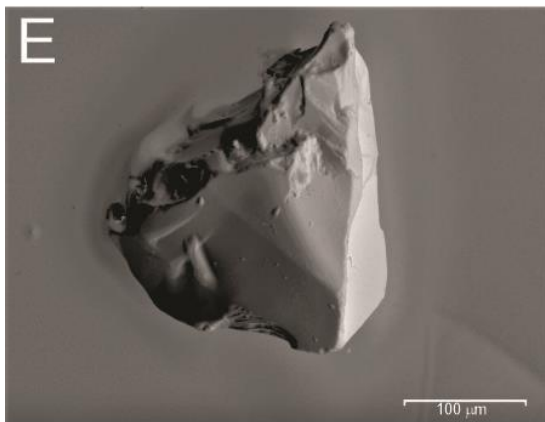
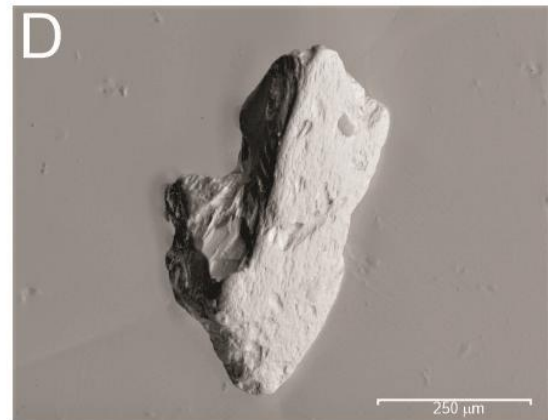
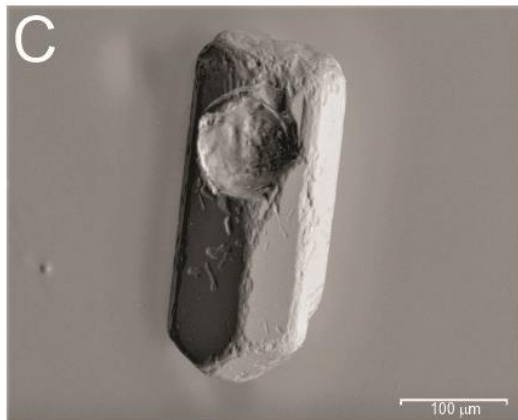
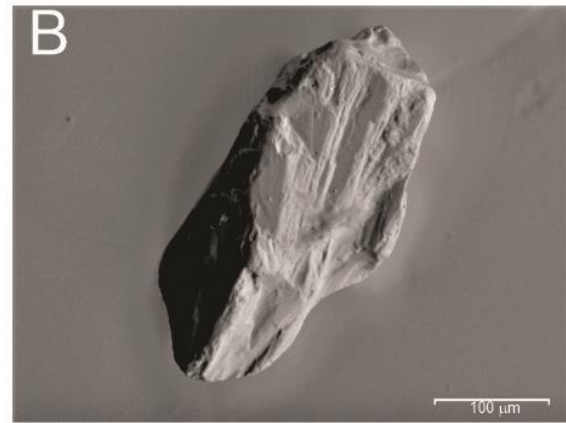
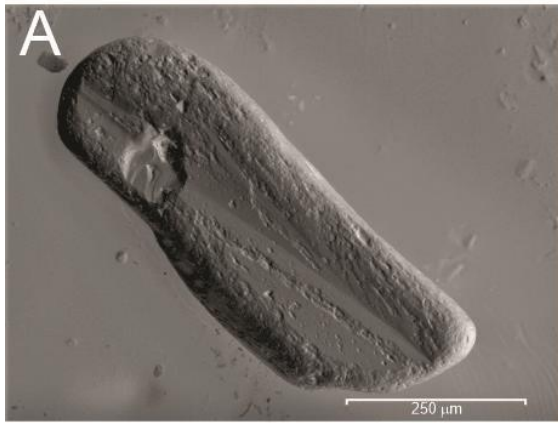


Figure 9 (previous page). New Zealand North Island site : A) foreshore $C = 0.67$, $D = 0.43$ elongated ; B) foreshore $C = 0.76$, $D = 0.23$, elongated angular C) stoss $C = 0.71$, $D = 0.23$, euhedral; D) leeface $C = 0.68$, $D = 0.41$ angular; E) foreshore $C = 0.71$, $D = 0.23$ angular; F) stoss $C = 0.87$, $D = 0.22$ subabraded G) leeface $C = 0.85$, $D = 0.39$ subabraded; H) foreshore $C = 0.91$, $D = 0.42$ abraded.

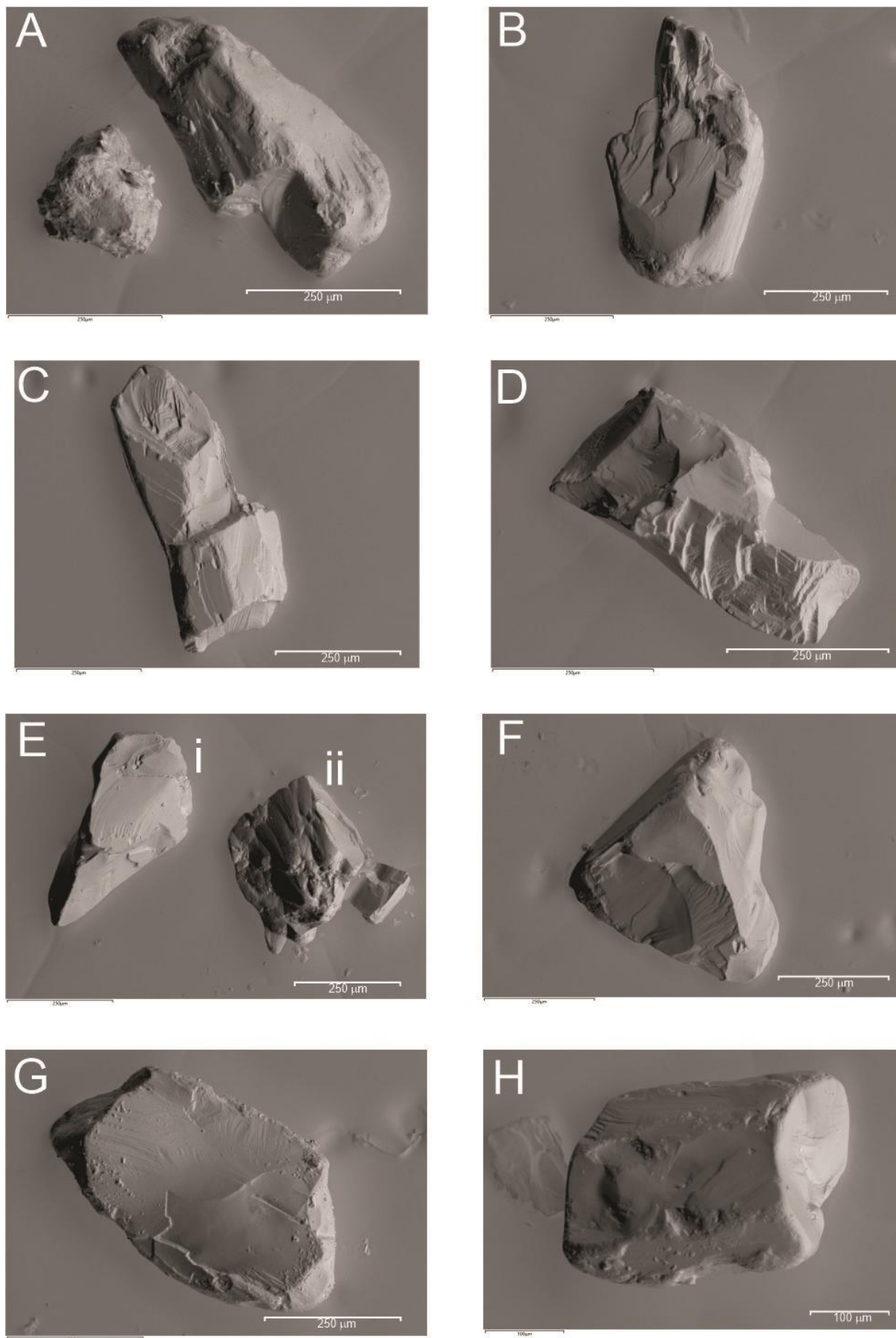


Figure 10. Santa Maria Island beach site: A) Formosa foreshore $C = 0.69$, $D = 0.36$ elongated ; B) Prahia 1 foreshore $C = 0.70$, $D = 0.39$, elongated angular C) Prahia 1 foreshore $C = 0.68$, $D = 0.35$, euhedral; D) Prahia 2 foreshore $C = 0.71$, $D = 0.29$ euhedral; E) Prahia 1 foreshore $C =$

0.56, D = 0.37 angular; F) Praia 1 foreshore C = 0.77, D = 51 subangular G) Praia 1 foreshore C = 0.85, D = 0.48 subabraded; H) Formosa foreshore C = 0.93, D = 0.34 subabraded to abraded.

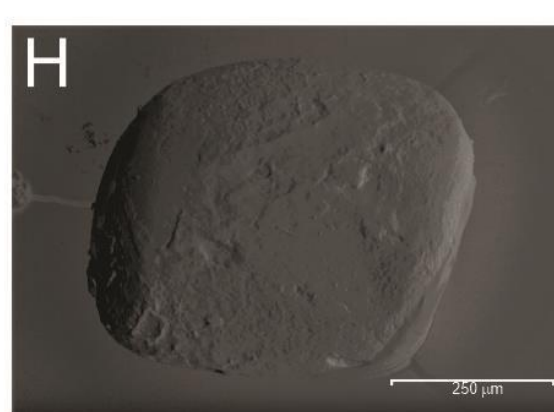
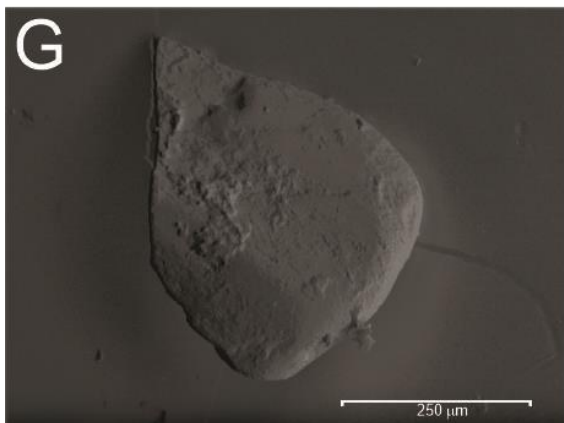
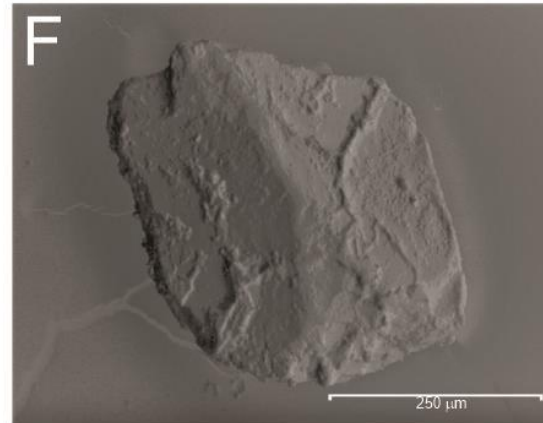
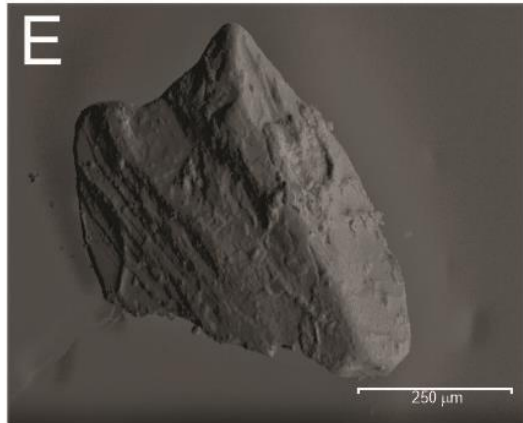
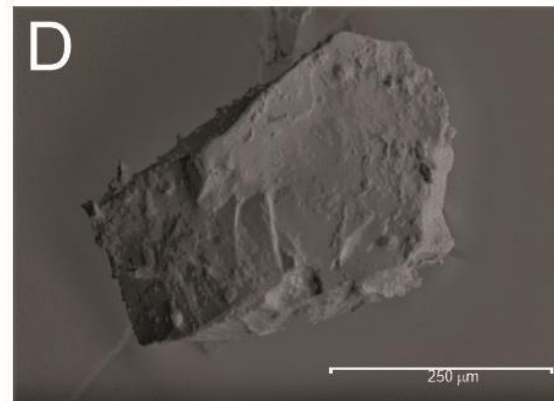
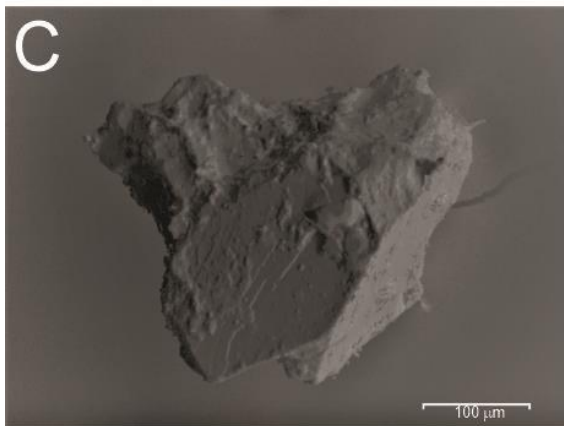
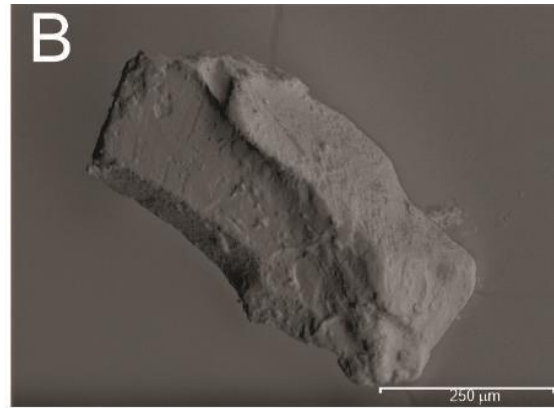
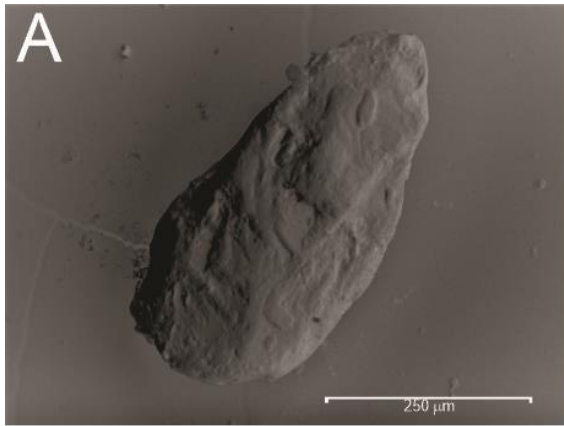


Figure 11 (previous page). Santa Maria Island paleobeach (Un) A) $C = 0.78$, $D = 0.35$ elongated; B) $C = 0.71$, $D = 0.45$, euhedral (?) C) $C = 0.68$, $D = 0.29$, angular; D) $C = 0.79$, $D = 0.37$ subangular; E) $C = 0.77$, $D = 0.49$ subangular; F) $C = 0.87$, $D = 31$ subabraded G) $C = 0.85$, $D = 0.39$ subabraded; H) $C = 0.93$, $D = 0.58$ abraded.

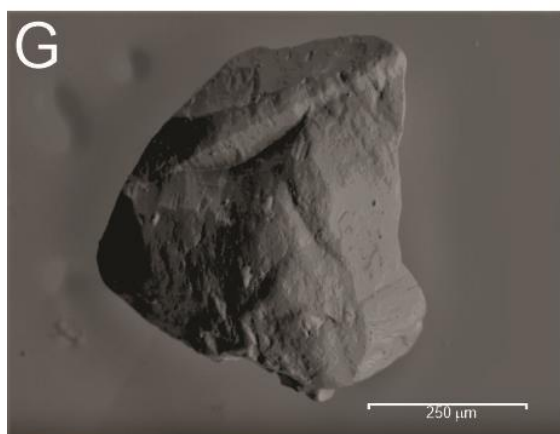
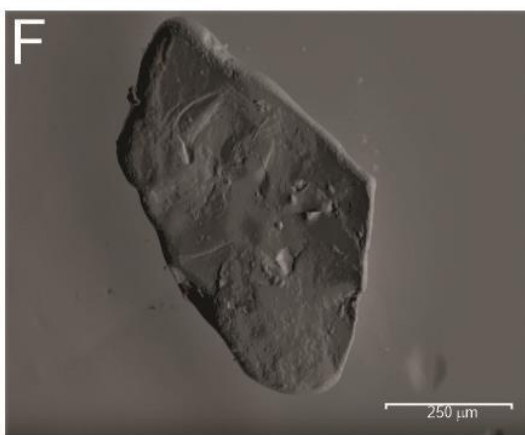
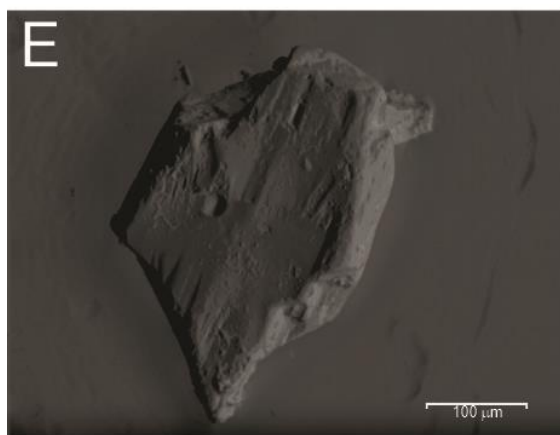
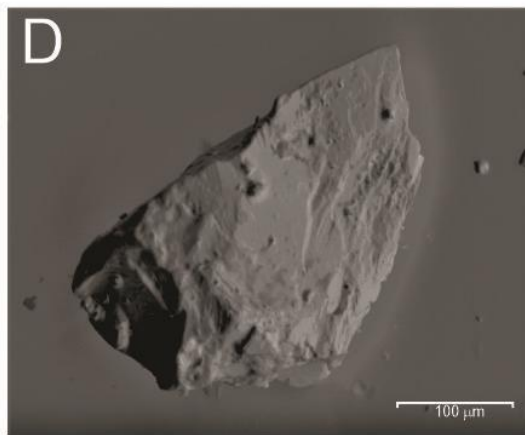
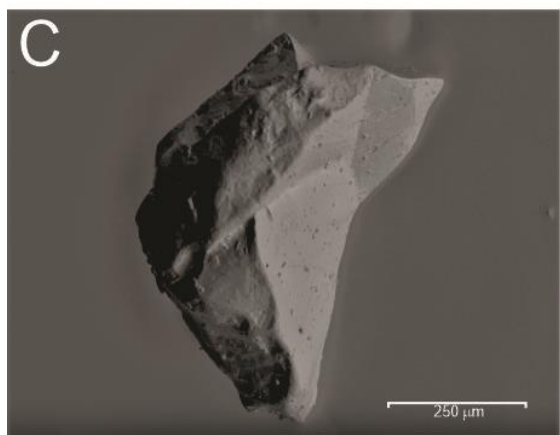
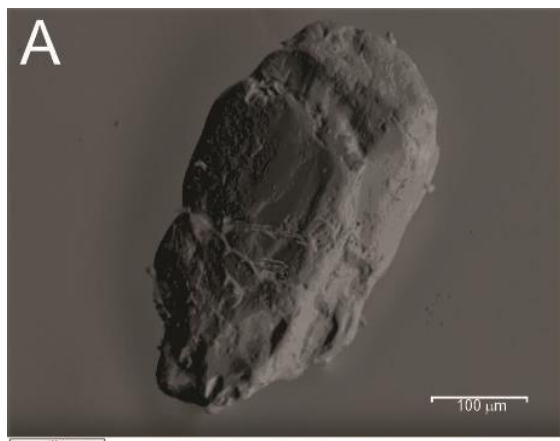


Figure 12 (previous page). Santa Maria Island paleobeach (W) A) $C = 0.75$, $D = 0.31$ elongated; B) $C = 0.73$, $D = 0.53$ elongated; C) $C = 0.64$, $D = 0.38$ elongated angular; D) $C = 0.76$, $D = 0.25$ subangular; E) $C = 0.73$, $D = 0.30$ angular; F) $C = 0.81$, $D = 0.58$ subabraded ; G) $C = 0.83$, $D = 0.51$ subabraded ; H) $C = 0.90$, $D = 0.25$ subabraded.

SITE	C values	Grain size range (mm)	Type (Wentworth grade)	Grain morphology
NZNI	0.52 - 0.80	0.18 - 0.49	fine to medium grain size	elongated, elongated angular, euhedral, angular
	0.80* - 0.90	0.16 - 0.49	fine to medium grain size	subabraded
	0.91 - 0.96	0.20 - 0.48	fine to medium grain size	abraded
SMI (beach sands)	0.52- 0.78	0.23 - 0.62	fine to coarse grain size	elongated, elongated angular, euhedral, angular, subangular
	0.78*- 0.88	0.20 - 0.48	fine to medium grain size	subabraded
	0.90 - 0.93	0.29 - 0.34	medium grain size	abraded
SMI paleobeach (Un)	0.52 - 0.80	0.27-0.91	medium to coarse grain size	elongated, elongated angular, euhedral, angular, subangular
	0.80*- 0.90*	0.24 - 0.65	fine to coarse grain size	subabraded
	0.92 - 0.94	0.33 - 0.59	medium to coarse grain size	abraded
SMI paleobeach (W)	0.64 – 0.79	0.23 – 0.58	Medium to coarse grain size	elongated, elongated angular, angular, subangular
	0.80 – 0.89	0.26 – 0.64	Fine to coarse grain size	subabraded
	0.90	0.25 – 0.40	Medium grain size	abraded

NZNI = New Zealand North Island ; SMI = Santa Maria Island; * C values corresponding to visually inspected grains with two apparent different morphologies.
Un = unwashed; W = washed

Table 1. Compactness values, grain size fractions and grain morphology of clinopyroxene grains.

NZNI	A	B	C	D	E	F	G	% correct
A	41	0	0	0	ab	7	0	85
B	14	0	0	0	ab	0	0	0
C	7	0	0	0	ab	0	0	0
D	5	0	0	0	ab	0	0	0
E	ab	ab	ab	ab	ab	ab	ab	ab
F	0	0	0	0	ab	41	0	100
G	0	0	0	0	ab	0	0	0
Correct	67	0	0	0	ab	51	0	Total 70
SMI								
A	0	3	0	1	0	1	0	0
B	0	16	0	5	0	3	0	66
C	0	3	0	0	0	0	0	0
D	0	16	0	3	0	1	0	15
E	0	0	0	0	0	7	0	0
F	0	0	0	0	0	28	0	100
G	0	0	0	0	0	2	0	0
Correct	0	38	0	9	0	42	0	Total 52
SMI paleobeach unwashed								
A	0	2	0	0	4	0	0	0
B	0	8	4	0	4	0	0	50
C	0	1	1	0	0	0	0	50
D	0	5	0	0	1	0	0	0
E	0	0	0	0	11	5	0	68
F	0	0	0	0	0	37	0	100
G	0	0	0	0	0	2	0	0
Correct	0	16	5	0	20	44	0	Total 67
SMI paleobeach washed								
A	3	3	ab	0	0	2	0	37
B	3	11	ab	0	0	0	0	78
C	ab	ab	ab	ab	ab	ab	ab	ab
D	0	4	ab	0	0	0	0	0
E	4	0	ab	0	0	1	0	0
F	0	0	ab	0	0	16	1	94
G	0	0	ab	0	0	0	2	100
Correct	10	18	ab	0	0	19	3	Total 64
Total simples								
A	41	31	1	0	0	15	0	46
B	31	47	6	0	0	11	0	49
C	3	8	3	0	0	1	0	20
D	14	21	1	0	0	1	0	0
E	12	0	0	0	0	28	0	0
F	0	0	0	0	0	162	0	100
G	0	0	0	0	0	14	0	0
Correct	101	107	11	0	0	232	0	Total 56

NZNI = New Zealand North Island; SMI = Santa Maria Island; A = elongated or large grains with negligible angular-pointed outlines, B = elongated angular or large grains with angular-pointed outlines C = euhedral or relatively pristine crystals, D = angular or small grain with angular-pointed outlines, E = subangular or small grain with less angular-pointed developed features, F = sub abraded or grains with some smooth grinding, G = abraded or grains with smooth outlines. Total samples = NZNI + SMI + SMI paleobeach; ab = absent. Bold type percentages are for the best classified groups.

Table 2. Percentages of a confusion matrix to classify clinopyroxene grains within a shape group.

References

- Allen, P.A., 2017. Sediment Routing Systems. Cambridge University Press. <https://doi.org/10.1017/9781316135754>
- Andò, S., Garzanti, E., Padoan, M., Limonta, M., 2012. Corrosion of heavy minerals during weathering and diagenesis: A catalog for optical analysis. *Sedimentary Geology*. 280, 165–178. <https://doi.org/10.1016/j.sedgeo.2012.03.023>
- Andrade, C., Trigo, R.M., Freitas, M.C., Gallego, M.C., Borges, P., Ramos, A.M., 2008. Comparing historic records of storm frequency and the North Atlantic Oscillation (NAO) chronology for the Azores region. *Holocene* 18, 745–754. <https://doi.org/10.1177/0959683608091794>
- Ávila, S.P., Johnson, M.E., Rebelo, A.C., Baptista, L., Melo, C.S., 2020. Comparison of Modern and Pleistocene (MIS 5e) Coastal Boulder Deposits from Santa Maria Island (Azores Archipelago, NE Atlantic Ocean). *Journal of Marine Science and Engineering* 8, 386. <https://doi.org/10.3390/jmse8060386>
- Ávila, S.P., Melo, C., Silva, L., Ramalho, R.S., Quartau, R., Hipólito, A., Cordeiro, R., Rebelo, A.C., Madeira, P., Rovere, A., Hearty, P.J., Henriques, D., Silva, C.M. da, Martins, A.M. de F., Zazo, C., 2015. A review of the MIS 5e highstand deposits from Santa Maria Island (Azores, NE Atlantic): palaeobiodiversity, palaeoecology and palaeobiogeography. *Quaternary Science Review* 114, 126–148. <https://doi.org/10.1016/j.quascirev.2015.02.012>
- Ávila, S.P., Ramalho, R.S., Habermann, J.M., Titschack, J., 2018. The Marine Fossil Record at Santa Maria Island (Azores). In: Kueppers, U. Beier, C. (Eds) *Volcanoes of the Azores. Active Volcanoes of the World* pp. 155–196. https://doi.org/10.1007/978-3-642-32226-6_9
- Baek, S., Jo, K., 2023. Surface microtextures of quartz grains and minor sedimentary components across the Paleolithic Jeongok-ri sediments, Yeoncheon, South Korea. *Journal of Quaternary Science* 38, 1142–1158. <https://doi.org/10.1002/jqs.3530>
- Bogaert, J., Rousseau, R., Van Hecke, P., Impens, I., 2000. Alternative area-perimeter ratios for measurement of 2D shape compactness of habitats. *Applied Mathematics and Computation* 111, 71–85. [https://doi.org/10.1016/S0096-3003\(99\)00075-2](https://doi.org/10.1016/S0096-3003(99)00075-2)
- Borges, P.A.V., Santos, A.M.C., Elias, R.B., Gabriel, R., 2020. The Azores Archipelago: Biodiversity Erosion and Conservation Biogeography. In: *Encyclopedia of the World's Biomes*. Elsevier, pp. 101–113. <https://doi.org/10.1016/B978-0-12-409548-9.11949-9>
- Borrelli, L., Antronico, L., Le Pera, E., Pisano, B., Sorriso-Valvo, M., 2021. Morphology, properties, and source of windblown sediments of the coastal dune field in the Gioia Tauro Plain, Calabria, southern Italy. *Catena* 201, 105193. <https://doi.org/10.1016/j.catena.2021.105193>
- Bouissonnié, A., Daval, D., Guyot, F., Ackerer, P., 2020. The Dissolution Anisotropy of Pyroxenes: Experimental Validation of a Stochastic Dissolution Model Based on Enstatite Dissolution. *The Journal of Physical Chemistry C* 124, 3122–3140. <https://doi.org/10.1021/acs.jpcc.9b10824>
- Brander, R.W., Short, A.D., 2000. Morphodynamics of a large-scale rip current system at Muriwai Beach, New Zealand. *Marine Geology* 165, 27–39. [https://doi.org/10.1016/S0025-3227\(00\)00004-9](https://doi.org/10.1016/S0025-3227(00)00004-9)
- Bribiesca, E., 2000. A measure of compactness for 3D shapes. *Computers & Mathematics with Applications* 40, 1275–1284. [https://doi.org/10.1016/S0898-1221\(00\)00238-8](https://doi.org/10.1016/S0898-1221(00)00238-8)
- Casey, W.H., Cheney, M.A., 1993. Bronsted reactions on oxide mineral surfaces and the temperature-dependence of their dissolution rates. *Aquatic Sciences* 55, 304–313. <https://doi.org/10.1007/BF00877275>
- Chaudhuri, D., Kushwaha, N., Sharif, I., Gohri, V., 2012. Unique Measure for Geometrical Shape Object Detection-based on Area Matching. *Defence Science Journal* 62, 58–66. <https://doi.org/10.14429/dsj.62.942>
- Costa, P.J.M., Andrade, C., Dawson, A.G., Mahaney, W.C., Freitas, M.C., Paris, R., Taborda, R., 2012. Microtextural characteristics of quartz grains transported and deposited by tsunamis and storms. *Sedimentary Geology* 275–276, 55–69. <https://doi.org/10.1016/j.sedgeo.2012.07.013>
- Dawn, E.J., DeVaughn, A.M., Marsaglia, K.M., 2007. Sand and gravel provenance in the Waipaoa River system: Sedimentary recycling in an actively deforming forearc basin, North Island, New Zealand, in: *Sedimentary Provenance and Petrogenesis: Perspectives from Petrography and Geochemistry*. Geological Society of America. [https://doi.org/10.1130/2006.2420\(16\)](https://doi.org/10.1130/2006.2420(16))

- Diepenbroek, M., Bartholoma, A., Ibbeken, H., 1992. How round is round? A new approach to the topic 'roundness' by Fourier grain shape analysis. *Sedimentology* 39, 411–422. <https://doi.org/10.1111/j.1365-3091.1992.tb02125.x>
- Dott, Jr., R.H., 2003. The Importance of Eolian Abrasion in Supermature Quartz Sandstones and the Paradox of Weathering on Vegetation-Free Landscapes. *Journal of Geology* 111, 387–405. <https://doi.org/10.1086/375286>
- Ebengo, D.M., de Boissieu, F., Vincent, G., Weber, C., Féret, J.-B., 2021. Simulating Imaging Spectroscopy in Tropical Forest with 3D Radiative Transfer Modeling. *Remote Sensing* 13, 2120. <https://doi.org/10.3390/rs13112120>
- Forbes, W.C., Starmer, R.J., 1974. Kaersutite is a possible source of alkali olivine basalts. *Nature* 250, 209–210. <https://doi.org/10.1038/250209a0>
- Foteinis, S., Campbell, J.S., Renforth, P., 2023. Life Cycle Assessment of Coastal Enhanced Weathering for Carbon Dioxide Removal from Air. *Environmental Science and Technology* 57, 6169–6178. <https://doi.org/10.1021/acs.est.2c08633>
- Garzanti, E., Andò, S., Padoan, M., Vezzoli, G., El Kammar, A., 2015a. The modern Nile sediment system: Processes and products. *Quaternary Science Reviews* 130, 9–56. <https://doi.org/10.1016/j.quascirev.2015.07.011>
- Garzanti, E., Andò, S., Vezzoli, G., Lustrino, M., Boni, M., Vermeesch, P., 2012. Petrology of the Namib Sand Sea: Long-distance transport and compositional variability in the wind-displaced Orange Delta. *Earth Science Reviews* 112, 173–189. <https://doi.org/10.1016/j.earscirev.2012.02.008>
- Garzanti, E., Resentini, A., Andò, S., Vezzoli, G., Pereira, A., Vermeesch, P., 2015b. Physical controls on sand composition and relative durability of detrital minerals during ultra-long distance littoral and aeolian transport (Namibia and southern Angola). *Sedimentology* 62, 971–996. <https://doi.org/10.1111/sed.12169>
- Graham, R.L., Yao, F.F., 1983. Finding the Convex Hull of a Simple Polygon. *Journal of Algorithms* 4, 324–331.
- Grandstaff, D.E., 1978. Changes in surface area and morphology and the mechanism of forsterite dissolution. *Geochimica et Cosmochimica Acta* 42, 1899–1901. [https://doi.org/10.1016/0016-7037\(78\)90245-4](https://doi.org/10.1016/0016-7037(78)90245-4)
- Hamill, P.F., Ballance, P.F., 1985. Heavy mineral rich beach sands of the Waitakere coast, Auckland, New Zealand. *New Zealand Journal of Geology and Geophysics* 28, 503–511. <https://doi.org/10.1080/00288306.1985.10421203>
- Hayward, B.W., 1976. Lower Miocene stratigraphy and structure of the Waitakere Ranges and the Waitakere Group (new). *New Zealand Journal of Geology and Geophysics* 19, 871–895. <https://doi.org/10.1080/00288306.1976.10420745>
- Heath, R.A., 1982. What drives the mean circulation on the New Zealand west coast continental shelf? *New Zealand Journal of Marine Freshwater Research* 16, 215–226. <https://doi.org/10.1080/00288330.1982.9515964>
- Heřmanská, M., Voigt, M.J., Marieni, C., Declercq, J., Oelkers, E.H. 2022. A comprehensive and internally consistent mineral dissolution rate database: Part I: Primary silicate minerals and glasses. *Chemical Geology*, 597, 120807 <https://doi.org/10.1016/j.chemgeo.2022.120807>
- Hernández, A., Kutiel, H., Trigo, R.M., Valente, M.A., Sigró, J., Cropper, T., Santo, F.E., 2016. New Azores archipelago daily precipitation dataset and its links with large-scale modes of climate variability. *International Journal of Climatology* 36, 4439–4454. <https://doi.org/10.1002/joc.4642>
- Immonen, N., 2013. Surface microtextures of ice-rafted quartz grains revealing glacial ice in the Cenozoic Arctic. *Palaeogeography, Palaeoclimatology Palaeoecology* 374, 293–302. <https://doi.org/10.1016/j.palaeo.2013.02.003>
- Itamiya, H., Sugita, R., Sugai, T., 2019. Analysis of the surface microtextures and morphologies of beach quartz grains in Japan and implications for provenance research. *Progress in Earth and Planetary Science* 6, 43. <https://doi.org/10.1186/s40645-019-0287-9>
- John, J.P., 1962. Electron Microscopy of Sand Surface Texture. *SEPM Journal of Sedimentary Research* Vol. 32. <https://doi.org/10.1306/74D70C59-2B21-11D7-8648000102C1865D>

- Johnsson, M.J., Ellen, S.D., McKittrick, M.A., 1993. Intensity and duration of chemical weathering: An example from soil clays of the southeastern Koolau Mountains, Oahu, Hawaii. In: Johnsson, M.J. Basu, A. (Eds.), *Processes Controlling the Composition of Clastic Sediments* pp. 147–170. <https://doi.org/10.1130/SPE284-p147>
- Kasper Zubillaga, J.J., 2009. Roundness in quartz grains from inland and coastal dune sands, Altar Desert, Sonora, Mexico. *Boletín de la Sociedad Geológica Mexicana* 61, 1–12. <https://doi.org/10.18268/BSGM2009v61n1a1>
- Kasper-Zubillaga, J.J., Arellano-Torres, E., Álvarez-Sánchez, L.F., Carlos Delgado, L., Martínez-Serrano, R.G., Baltazar-Jiménez, P.A.E., 2022. Implications of polymodal distributions in the grain size parameters of coastal dune sands (Oaxaca, Mexico). *Sedimentary Geology* 437, 106189. <https://doi.org/10.1016/j.sedgeo.2022.106189>
- Kasper-Zubillaga, J.J., Dickinson, W.W., Carranza-Edwards, A., Hornelas-Orozco, Y., 2005. Petrography of quartz grains in beach and dune sands of Northland, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics* 48, 649–660. <https://doi.org/10.1080/00288306.2005.9515139>
- Kasper-Zubillaga, J.J., Martínez-Serrano, R.G., Arellano-Torres, E., Álvarez Sánchez, L.F., Andrade Patiño, D., González Bermúdez, A., Carlos-Delgado, L., 2021. Petrographic and geochemical analyses of dune sands from southeastern Mexico, Oaxaca, Mexico. *Geological Journal*. <https://doi.org/10.1002/gj.4086>
- Kasper-Zubillaga, J.J., Martínez-Serrano, R.G., Buchs, D.M., Mendieta-Lora, M., Arellano-Torres, E., Álvarez-Sánchez, L.F., 2023. Surface textures of detrital pyroxenes in coastal dune sands (western Gulf of Mexico, Mexico): Implications for their preservation and geoenvironmental processes. *The Depositional Record* 9, 789–809. <https://doi.org/10.1002/dep2.228>
- Knauss, K.G., Nguyen, S.N., Weed, H.C., 1993. Diopside dissolution kinetics as a function of pH, CO₂, temperature, and time. *Geochimica et Cosmochimica Acta* 57, 285–294. [https://doi.org/10.1016/0016-7037\(93\)90431-U](https://doi.org/10.1016/0016-7037(93)90431-U)
- Krastel, S., Schmincke, H., Jacobs, C., 2001. Formation of submarine canyons on the flanks of the Canary Islands. *Geo-Marine Letters* 20, 160–167. <https://doi.org/10.1007/s003670000049>
- Krinsley, D., Doorkamp, J.C., 1973. *Atlas of quartz sand surface textures*, England 91. Cambridge University Press p 37
- Krinsley, D.H., Donahue, J., 1968. Environmental Interpretation of Sand Grain Surface Textures by Electron Microscopy. *Geological Society of America Bulletin* 79, 743–748. [https://doi.org/10.1130/0016-7606\(1968\)79\[743:EIOGSJ\]2.0.CO;2](https://doi.org/10.1130/0016-7606(1968)79[743:EIOGSJ]2.0.CO;2)
- Kuenen, P.H., 1959. Experimental abrasion; 3, Fluvial action on sand. *American Journal of Science* 257, 172–190. <https://doi.org/10.2475/ajs.257.3.172>
- Kuenen, Ph.H., 1960. Experimental Abrasion 4: Eolian Action. *Journal of Geology* 68, 427–449. <https://doi.org/10.1086/626675>
- Larrea, P., França, Z., Widom, E., Lago, M., 2018. Petrology of the Azores Islands. In: Kueppers, U., Beier, C. (Eds.), *Volcanoes of the Azores. Active Volcanoes of the World*. Springer, Berlin, Heidelberg. pp. 197–249. https://doi.org/10.1007/978-3-642-32226-6_10
- Le Pera, E., Morrone, C., 2020. The use of mineral interfaces in sand-sized volcanic rock fragments to infer mechanical durability. *Journal of Palaeogeography* 9, 21. <https://doi.org/10.1186/s42501-020-00068-8>
- Le Pera, E., Morrone, C., Arribas, J., Arribas, M.E., Ancochea, E., Huertas, M.J., 2021. Petrography and provenance of beach sands from volcanic oceanic islands: Cabo Verde, Atlantic Ocean. *Journal of Sedimentary Research* 91, 92–115. <https://doi.org/10.2110/jsr.2020.096>
- Le Pera, E., Quartau, R., Moreira, S., Ramalho, R., Rodrigues, A., 2023. Petrography and provenance of Santa Maria Island shelf sand, Azores., in: *SIMP-SGI-AIV-SOGEI 2023 Congress*, Potenza (Italy). p. 752.
- Leterrier, J., Maury, R.C., Thonon, P., Girard, D., Marchal, M., 1982. Clinopyroxene composition as a method of identification of the magmatic affinities of paleo-volcanic series. *Earth and Planetary Science Letters* 59, 139–154. [https://doi.org/10.1016/0012-821X\(82\)90122-4](https://doi.org/10.1016/0012-821X(82)90122-4)
- Lewis, C.A., Armstrong, G.A.S., 1994. An evaluation of different methods of preparation of quartz grains for study of their surface features by scanning electron microscopy. *Acta Microscopia* 99–105.

- Li, W., Goodchild, M.F., Church, R., 2013. An efficient measure of compactness for two-dimensional shapes and its application in regionalization problems. *International Journal of Geographical Information Science* 27, 1227–1250. <https://doi.org/10.1080/13658816.2012.752093>
- McKinley, J.M., Worden, R.H., Ruffell, A.H., 2003. Smectite in sandstones: a review of the controls on occurrence and behaviour during diagenesis. In: Worden, R.H. and Morad. *Clay Mineral Cements in Sandstones*. International Association of Sedimentologists. Special Publication 34, 109–128
- Madhavaraju, J., García y Barragán, J.C., Mohammad Hussain, S., Pachaiveedu Mohan, S., 2009. Microtextures on quartz grains in the beach sediments of Puerto Peñasco and Bahía Kino, Gulf of California, Sonora, Mexico. *Revista Mexicana de Ciencias Geológicas* 26, 367–379.
- Mahaney, W.C., 2002. *Atlas of Sand Grain Surface Textures and Applications*. Oxford University Press 237.
- Makvandi, S., Beaudoin, G., McClenaghan, B.M., Layton-Matthews, D., 2015. The surface texture and morphology of magnetite from the Izok Lake volcanogenic massive sulfide deposit and local glacial sediments, Nunavut, Canada: Application to mineral exploration. *Journal of Geochemical Exploration* 150, 84–103. <https://doi.org/10.1016/j.gexplo.2014.12.013>
- Marques, F.O., Hildenbrand, A., Costa, A.C.G., Sibrant, A.L.R., 2020. The evolution of Santa Maria Island in the context of the Azores Triple Junction. *Bulletin of Volcanology* 82, 39. <https://doi.org/10.1007/s00445-020-01378-4>
- Marsaglia, K. M. 1993. Basaltic island sand provenance. In: Johnsson, M. J., Basu, A. (Eds.), *Processes Controlling the Composition of Clastic Sediments* pp. 41–65. Geological Society of America Bulletin, Special Paper 284.
- Mejía-Ledezma, R.O., Kasper-Zubillaga, J.J., Alvarez-Sánchez, L.F., Mendieta-Lora, M., Arellano-Torres, E., Tedlalmatzi-Martínez, J.L., Gonzalez-Bermúdez, A., Patiño-Andrade, D., Armstrong-Altrin, J.S., 2020. Surface textures of quartz and ilmenite grains from dune and beach sands of the Gulf of Mexico Coast, Mexico: Implications for fluvial, aeolian and marine transport. *Aeolian Research* 45, 100611. <https://doi.org/10.1016/j.aeolia.2020.100611>
- Melo, I., Neto Torres, J.P., Ferreira Fernandes, C.A., Marques Lameirinhas, R.A., 2020. Sustainability economic study of the islands of the Azores archipelago using photovoltaic panels, wind energy and storage system. *Renewables Wind, Water, and Solar* 7, 4. <https://doi.org/10.1186/s40807-020-00061-8>
- Mo, P.-Q., 2020. Internal rolling method for particle shape evaluation and reconstruction. *PLOS ONE* 15, e0242162. <https://doi.org/10.1371/journal.pone.0242162>
- Monasterio-Guillot, L., Rodríguez-Navarro, C., Ruiz-Agudo, E., 2021. Kinetics and Mechanisms of Acid-pH Weathering of Pyroxenes. *Geochemistry, Geophysics, Geosystems* 22. <https://doi.org/10.1029/2021GC009711>
- Montero, R.S., Bribiesca, E., 2009. State of the art of compactness and circularity measures. *International Mathematical Forum* 4, 1305–1335.
- Moral-Cardona, J.P., Gutiérrez-Mas, J.M., Sánchez-Bellón, A., Domínguez-Bella, S., Martínez-López, J., 2005. Surface textures of heavy-mineral grains: a new contribution to provenance studies. *Sedimentary Geology* 174, 223–235. <https://doi.org/10.1016/j.sedgeo.2004.12.006>
- Morrone, C., Le Pera, E., De Rosa, R., Marsaglia, K.M., 2018. Heavy minerals distribution and provenance in modern beach sands of Campania, Italy. *Rendiconti Online della Società Geologica Italiana* 45, 141–146. <https://doi.org/10.3301/ROL.2018.42>
- Morrone, C., Le Pera, E., Marsaglia, K.M., De Rosa, R., 2020. Compositional and textural study of modern beach sands in the active volcanic area of the Campania region (southern Italy). *Sedimentary Geology* 396, 105567. <https://doi.org/10.1016/j.sedgeo.2019.105567>
- Morton, A.C., Hallsworth, C., 2007. Chapter 7 Stability of Detrital Heavy Minerals During Burial Diagenesis. Mange, M.A., Wright, D.T. (Eds.), *Heavy Minerals in Use*. pp. 215–245. [https://doi.org/10.1016/S0070-4571\(07\)58007-6](https://doi.org/10.1016/S0070-4571(07)58007-6)
- Noack, Y., Colin, F., Nahon, D., Delvigne, J., Michaux, L., 1993. Secondary-mineral formation during natural weathering of pyroxene; review and thermodynamic approach. *American Journal of Science* 293, 111–134. <https://doi.org/10.2475/ajs.293.2.111>

- Norton, 1985. A multivariate technique for estimating New Zealand temperature normals. *Weather and Climate* 5, 64. <https://doi.org/10.2307/44279988>
- Oakey, R.J., Green, M., Carling, P.A., Lee, M.W.E., Sear, D.A., Warburton, J., 2005. Grain-Shape Analysis--A New Method for Determining Representative Particle Shapes for Populations of Natural Grains. *Journal of Sedimentary Research* 75, 1065–1073. <https://doi.org/10.2110/jsr.2005.079>
- Osserman, R., 1978. The isoperimetric inequality. *Bulletin of the American Mathematical Society* 84, 1182–1238. <https://doi.org/10.1090/S0002-9904-1978-14553-4>
- Phillips-Lander, C.M., Legett, C., Elwood Madden, A.S., Elwood Madden, M.E., 2017. Can we use pyroxene weathering textures to interpret aqueous alteration conditions? Yes and No. *American Mineralogist* 102, 1915–1921. <https://doi.org/10.2138/am-2017-6155>
- Pickrill, R.A., Mitchell, J.S., 1979. Ocean wave characteristics around New Zealand. *New Zealand Journal of Marine Freshwater Research* 13, 501–520. <https://doi.org/10.1080/00288330.1979.9515827>
- Price, R.C., Stewart, R.B., Woodhead, J.D., Smith, I.E.M., 1999. Petrogenesis of High-K Arc Magmas: Evidence from Egmont Volcano, North Island, New Zealand. *Journal of Petrology* 40, 167–197. <https://doi.org/10.1093/petroj/40.1.167>
- Quartau, R., Tempera, F., Mitchell, N.C., Pinheiro, L.M., Duarte, H., Brito, P.O., Bates, C.R., Monteiro, J.H., 2012. Morphology of the Faial Island shelf (Azores): The interplay between volcanic, erosional, depositional, tectonic and mass-wasting processes. *Geochemistry, Geophysics, Geosystems* 13. <https://doi.org/10.1029/2011GC003987>
- Ramalho, R.S., Helffrich, G., Madeira, J., Cosca, M., Thomas, C., Quartau, R., Hipólito, A., Rovere, A., Hearty, P.J., Ávila, S.P., 2017. Emergence and evolution of Santa Maria Island (Azores)—The conundrum of uplifted islands revisited. *Geological Society of America Bulletin* 129, 372–390. <https://doi.org/10.1130/B31538.1>
- Ramer, U., 1972. An iterative procedure for the polygonal approximation of plane curves. *Computer Graphics and Image Processing* 1, 244–256. [https://doi.org/10.1016/S0146-664X\(72\)80017-0](https://doi.org/10.1016/S0146-664X(72)80017-0)
- Reddad, H., El Talibi, H., Perri, F., El Moussaoui, S., Zerdeb, M.A., Zaghloul, M.N., Critelli, S., 2016. Textural and compositional controls on modern fluvial and beach sands of Mediterranean coastal Rif belt (Northern Rif, Morocco). *Italian Journal of Geosciences* 135, 336–349. <https://doi.org/10.3301/IJG.2015.33>
- Resentini, A., Andò, S., Garzanti, E., 2018. Quantifying Roundness of Detrital Minerals by Image Analysis: Sediment Transport, Shape Effects, and Provenance Implications. *Journal of Sedimentary Research* 88, 276–289. <https://doi.org/10.2110/jsr.2018.12>
- Ricchi, A., Quartau, R., Ramalho, R.S., Romagnoli, C., Casalbore, D., Zhao, Z., 2020. Imprints of volcanic, erosional, depositional, tectonic and mass-wasting processes in the morphology of Santa Maria insular shelf (Azores). *Marine Geology* 424, 106163. <https://doi.org/10.1016/j.margeo.2020.106163>
- Roduit, N., 2019. JMicroVision: Image analysis toolbox for measuring and quantifying components of high-definition images. Software Version 1.3.1.
- Roduit, N., 2007. JMicroVision: un logiciel d'analyse d'images pétrographiques polyvalent. *Terre et Environnement*.
- Rosenfeld, A., 1974. Compact Figures in Digital Pictures. *IEEE Transactions on Systems, Man, and Cybernetics* SMC-4, 221–223. <https://doi.org/10.1109/TSMC.1974.5409121>
- Russell, R.D., Taylor, R.E., 1937. Roundness and Shape of Mississippi River Sands. *Journal of Geology* 45, 225–267.
- Rusu, L., Guedes Soares, C., 2012. Wave energy assessments in the Azores islands. *Renewable Energy* 45, 183–196. <https://doi.org/10.1016/j.renene.2012.02.027>
- Serralheiro, A., Alves, C.A.M., Forjaz, V.H., Rodrigues, B., 1987. Carta Vulcanológica dos Açores. Ilha de Santa Maria na (folhas 1 e 2), scale 1:15,000.
- Serralheiro, A., Madeira, J., 1993. Stratigraphy and Geochronology of Santa Maria Island (Azores). *Açoreana* 7, 575–592.
- Short, A., 2003. Australia beach systems - The morphodynamics of wave through tide-dominated beach-dune systems. *Journal of Coastal Research* 35, 7–20.

- Sibrant, A.L.R., Hildenbrand, A., Marques, F.O., Costa, A.C.G., 2015. Volcano-tectonic evolution of the Santa Maria Island (Azores): Implications for paleostress evolution at the western Eurasia–Nubia plate boundary. *Journal of Volcanology and Geothermal Research* 291, 49–62. <https://doi.org/10.1016/j.jvolgeores.2014.12.017>
- Tangari, A.C., Le Pera, E., Andò, S., Garzanti, E., Piluso, E., Marinangeli, L., Scarciglia, F., 2021. Soil-formation in the central Mediterranean: Insight from heavy minerals. *Catena* 197, 104998. <https://doi.org/10.1016/j.catena.2020.104998>
- Thomas, M.C., Wiltshire, R.J., Williams, A.T., 1995. The use of Fourier descriptors in the classification of particle shape. *Sedimentology* 42, 635–645. <https://doi.org/10.1111/j.1365-3091.1995.tb00397.x>
- Tunwal, M., Mulchrone, K.F., Meere, P.A., 2018. Quantitative characterization of grain shape: Implications for textural maturity analysis and discrimination between depositional environments. *Sedimentology* 65, 1761–1776. <https://doi.org/10.1111/sed.12445>
- Turner, G., Morton, A.C., 2007. The Effects of Burial Diagenesis on Detrital Heavy Mineral Grain Surface Textures. Mange, M.A., Wright, D.T. (Eds.), *Heavy Minerals in Use*. pp. 393–412. [https://doi.org/10.1016/S0070-4571\(07\)58014-3](https://doi.org/10.1016/S0070-4571(07)58014-3)
- Varghese, T., Prakash, T., 2016. Depositional History of Coastal Plain Sediments, Southern Kerala, South West India. *Journal of Earth Science and Climatic Change* 7. <https://doi.org/10.4172/2157-7617.1000355>
- Velbel, M.A., 2007. Surface Textures and Dissolution Processes of Heavy Minerals in the Sedimentary Cycle: Examples from Pyroxenes and Amphiboles. In: Mange, M.A., Wright, D.T. (Eds.), *Heavy Minerals in Use* pp. 113–150. [https://doi.org/10.1016/S0070-4571\(07\)58004-0](https://doi.org/10.1016/S0070-4571(07)58004-0)
- Velbel, M.A., 1993. Formation of protective surface layers during silicate-mineral weathering under well-leached, oxidizing conditions. *American Mineralogist* 78, 405–414.
- Velbel, M.A., Barker, W.W., 2008. Pyroxene Weathering to Smectite: Conventional and Cryo-Field Emission Scanning Electron Microscopy, Koua Bocca Ultramafic Complex, Ivory Coast. *Clays Clay Mineralogy* 56, 112–127. <https://doi.org/10.1346/CCMN.2008.0560110>
- Velbel, M.A., Ranck, J.M., 2008. Etch pits on naturally altered olivine from dunites of the Appalachian Blue Ridge Mountains, North Carolina, USA. *Mineralogical Magazine* 72, 145–148. <https://doi.org/10.1180/minmag.2008.072.1.145>
- Violante, P., Wilson, M.J., 1983. Mineralogy of some Italian andosols with special reference to the origin of the clay fraction. *Geoderma* 29, 157–174. [https://doi.org/10.1016/0016-7061\(83\)90039-3](https://doi.org/10.1016/0016-7061(83)90039-3)
- Vos, K., Vandenberghe, N., Elsen, J., 2014. Surface textural analysis of quartz grains by scanning electron microscopy (SEM): From sample preparation to environmental interpretation. *Earth Science Reviews* 128, 93–104. <https://doi.org/10.1016/j.earscirev.2013.10.013>
- Wadell, H., 1932. Volume, Shape, and Roundness of Rock Particles. *Journal of Geology* 40, 443–451. <https://doi.org/10.1086/623964>
- Wilson, M.J., 2004. Weathering of the primary rock-forming minerals: processes, products and rates. *Clay Mineralogy* 39, 233–266. <https://doi.org/DOI: 10.1180/0009855043930133>
- Yhasnara, M., Costa, P.J.M., Dourado, F., Martins, M.V.A., Feist, L., Bellanova, P., Reicherter, K., 2023. Microtextural signatures in quartz grains and foraminifera from tsunami deposits of the Portuguese shelf. *Geo-Marine Letters* 43, 5. <https://doi.org/10.1007/s00367-023-00747-0>
- Yock, D., 1973. A study of the beach and dune sands from Muriwai to Kaipara South Head. Thesis (MA Geology) University of Auckland.
- Zhao, B., Wang, J., 2016. 3D quantitative shape analysis on form, roundness, and compactness with μ CT. *Powder Technology* 291, 262–275. <https://doi.org/10.1016/j.powtec.2015.12.029>
- Zingg, T., 1935. Beitrag zur Schotteranalyse: Schweizerische Mineralogische und Petrologische Mitteilungen (Doctoral Thesis). ETH Zürich.