AEOLIAN ABRASION OF THE COASTAL DEPOSITS ON THE WESTERN CRETE

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Abstract: Crete is located in the collision zone of tectonic plates; therefore, the island coast was often shaped due to tectonic phenomena. In 365 AD, a major earthquake caused the uplift of the coast of western Crete by a few metres. It means that the modern beaches of this part of the island are fragments of the former seabed with its littoral deposits. Some of these deposits are affected by wind activity. The article aims to answer the question, did wind transport lasting more than 1600 years give the marine deposits the features of aeolian deposits? Grain size and mineral composition were determined for samples from seven research sites in western Crete. Deposits representing three sedimentary environments were examined – high-energy beach, aeolian, and beach with permanent or periodic fluvial supply. Quartz abrasion was established using the morphoscopic method. In the 0.8–1.0 mm fraction, less resistant carbonate minerals dominate (on average, 77%), while the content of more resistant quartz is low (on average, 18%). It means most deposits are relatively young and were briefly in the range of aeolian processes. Coastal deposits are dominated by moderately rounded and mat grains EM/RM, on average 79%. The content of very well-rounded and mat grains RM is low, on average 18%. Multiple predominances of EM/RM grains in relation to RM grains indicate short-term aeolian transport. It can be concluded that the degree of aeolisation of coastal deposits by wind activity from 365 AD to the present is weak, at most moderate.

Key words: coastal deposits, aeolian processes, quartz abrasion, morphoscopic method, Crete

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Introduction

Crete is located in one of the Mediterranean Sea's most seismically active regions – in the African plate's subduction zone under the Aegean microplate. The island coast was, therefore, often shaped as a result of violent tectonic phenomena, mainly earthquakes. These changes included uplift/subsidence and the tsunami's rapid displacement of coastal deposits.

In historical times, namely between the 4th and 6th centuries AD, there occurred a period of unusually high seismic activity, referred to as the early Byzantine tectonic paroxysm (Pirazzoli 1986). In 365 AD, near the south-western coast of Crete, the epicentre of a major earthquake measuring 8.3 on the Richter scale (Pararas-Carayannis, Mader 2010) caused a significant upward displacement of the earth's crust (Thommeret et al. 1981, Pirazzoli et al. 1996a, b, Price et al. 2002). The coast of western Crete was elevated by an average of 6.66 m above sea level, with a maximum of 9.15 ± 0.20 m, according to the results obtained in the study of Mourtzas et

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al. (2015). Stiros (2010) states that all subsequent earthquakes were events of much smaller scale and modified the coastal landscape formed by the 365 AD earthquake relatively little. The sea level then was –1.25 ± 0.05 m, and the current level was stabilised during two episodes of subsidence: the first by 0.70 m due to the 1604 earthquake; and the second by 0.55 m during the last 400 years (Mourtzas et al. 2015).

The coast of Crete was also within reach of the tsunami. Papadopoulos (2011) documented 19 extreme tsunamis, caused mainly by earthquakes but also by the eruption of the Thera volcano (Santorini). The coastal geomorphology was strongly influenced by five tsunamis that occurred in the following years, listed here in the order of youngest to oldest: 1965 AD, 1650 AD, 1303 AD, 365 AD and 1628 BC (Thommeret et al. 1981, Pirazzoli 1986, Stiros 2001, Scheffers, Scheffers 2007, Werner et al. 2018). According to Pearson et al. (2018), the last of the mentioned dates (1628 BC), referring to the tsunami caused by the eruption of the Thera volcano, should be moved from the 17th to the 16th century BC.

One of the geomorphological consequences of these geological phenomena is that the modern beaches of western Crete are fragments of the former seabed with its littoral deposits. Some of these deposits have been subjected to wind activity for several centuries. Morphological manifestations of aeolian processes, from fine ripplemarks to dunes, are observed in various parts of the west coast of Crete. One may ask whether these deposits already have the characteristics of aeolian deposits. Did wind activity lasting more than 1500 years give the marine deposits the features of aeolian deposits? An attempt to answer this question is the purpose of this article.

Coastal processes and deposits are widely described in the world literature, for example Carter (1988), Bird (2000), Nordstrom (2000), Carvalhido et al. (2014), Łabuz et al. (2018), and Bertran and Fouéré (2020). Studies referring directly or indirectly to aeolian abrasion of coastal deposits are conducted in various parts of the world, and in different climatic, geological and geomorphological conditions (Setlow 1978, Mycielska-Dowgiałło 1988, Araújo 1994, Pyökäri 1999, Kurowski 2002, Cherian et al. 2004, Kasper-Zubillaga et al. 2005, Kasper-Zubillaga 2009, Costa et al. 2012, Dullek, Olszak 2013, Garzanti et al. 2015, Bellanova et al. 2016, Whitmore, Strom 2017, Kalińska-Nartiša et al. 2018). The degree of quartz abrasion is determined by different methods and for different fractions, which makes direct comparison of results difficult. Still, the quartz grains from the aeolian environment are generally more rounded and matted than source deposits from the high-energy beach environment.

The beach deposits of Crete have been the subject of a detailed study by Pyökäri (1999). The author presented a broad set of data on coastal deposits' texture, composition and roundness for 22 beaches (with and without dunes) located in the western and eastern parts of the island. In the context of the question posed above, three statements by Pyökäri (1999) are relevant: (1) less resistant carbonate deposits predominate over more resistant non-carbonate deposits on many beaches; (2) less resistant carbonate grains have better roundness than more resistant quartz grains; and (3) textural features of beach deposits are the result of local environmental conditions and the influence of coastal drift determined by the prevailing winds and waves.

Despite a comprehensive presentation of the characteristics of beach deposits in the cited work, there are no references to the degree of their roundness due to the aeolian process, and even more so as a function of the duration of this process. Roundness is presented as one of the characteristics of deposits without specifying their origin. In addition, the Powers method (1953) used by the author is based on an analysis of only the grain shape without providing information about the nature of its surface, although the latter of these is a feature used in several studies of the aeolian environment (e.g. Goździk 1980, Mycielska-Dowgiałło, Woronko 1998, Woronko 2012, Zieliński 2016, Dulias 2023). For the above reasons, in this study, the degree of quartz grain rounding and matting was determined using the Cailleux (1942) method, as modified by Mycielska-Dowgiałło and Woronko (1998). The aim was to examine deposits representing three sedimentary environments – high-energy beach, aeolian, and beach with permanent or periodic fluvial supply, and to determine the differences between them regarding aeolian abrasion of quartz grains. To our knowledge, this is the first analysis of this type for coastal deposits in Crete.

Study area

Crete is the largest island of Greece, located in the Eastern Mediterranean. The island was formed from rising underwater mountain ranges. It is located in the collision zone of tectonic plates; therefore, numerous earthquakes occur here.

Crete is built of various rocks – limestones, dolomites, phyllites, quartzites, sandstones and volcanic rocks. Crete is predominantly mountainous (Timios Stavros – 2456 m above sea level) and is fragmented by numerous deep, rocky gorges. The island's shores, over a 1000 km long, are rocky and interspersed with quite wide beaches. Due to its latitudinally elongated shape, the island is divided into a western and an eastern part. The research was carried out in the western region (Fig. 1).

Most of Crete has a Mediterranean climate – summers are hot and dry, and winters are cool. Some mountain peaks are covered with snow for most of the year. The average annual rainfall is about 640 mm. Generally, north-westerly and northerly winds predominate. The highest tides are around 0.3 m, and during storms, the sea level rises more than 1 m (Pyökäri 1999). The southern part of Crete belongs to the North African climate zone.

Materials and methods

In the present study, the term coastal deposits has been treated as a reference to deposits occurring on the coast. Attention was focussed on deposits that are at least periodically exposed to wind transport, that is to say from the backshore and coastal dunes. Site selection criteria also varied depending upon the parameters of uplift scale, lithology and coastal morphology,

Fig. 1. Location of research sites on the coast of western Crete.

Table 1. Uplift and geomorphology of the research sites.

Site	Name	Uplift of the 365 AD earthquake [m]			Geomorphology
		Flemming 1978	Kelletat 1991	Pirazzoli et al. 1996b	
1	Seitan Limania	0–1	0	1–2	Backshore in a narrow rocky bay with a rocky gorge with periodic flow
2	Stavros	0–1	0	1–2	Backshore in a wide bay outside the mouth of a periodic river
3	Balos	6–7	6	5.5–6	Backshore in a wide bay and field of the aeolian sands on the cliff
4	Elafonisi	8–9	9	> 9	Backshore and dunes on a small island
5	Orthi Ammos	2–3	2	3	Backshore and dunes on the cliff
6	Preveli	0–1	0	1–2	Backshore with the mouth of a permanent river from a deep rocky gorge
7	Matala	0–1	0	< 1	Backshore in a wide rocky bay outside the mouth of a periodic river

including the presence or absence of a river mouth (permanent or periodic) (Table 1).

According to the above criteria, seven research sites located in the western part of Crete were established. They are: Seitan Limania, Stavros, Balos, Elafonisi, Orthi Ammos, Preveli and Matala (Fig. 1). One of the conditions of aeolian transport is the drying of deposits, which is why, on the coasts, this process can start in the backshore, which is submerged only during the highest tides and severest storms, and then it is also supplied with fresh marine material. In the study area, the sites located in this zone are Balos 1, Elafonisi 1, Orthi Ammos 1 and Stavros. The last of the mentioned sites is located on the coast with the mouth of a periodic watercourse, but it was established at a distance excluding the supply of fluvial material. Thus, the characteristics of the deposits from the mentioned sites represent the local high-energy beach environment. Three more sites – Seitan Limania, Preveli and Matala – are also located on the backshore, but the first is at the mouth of a gorge with periodic water flow, the second at the mouth of a permanent river from a large and deep rocky gorge, and the third close to the mouth of a periodic river. At these sites, beach deposits are constantly or periodically fed with fluvial deposits. Six sites were established within the deposits of aeolian origin – Elafonisi 2 in a dune on a small offshore island, Orthi Ammos 2 in a dune encroaching on a cliff and Balos 2–5 in an aeolian sand field on a cliff.

Samples weighing 200–400 g were collected from the surface, usually 2–3 at individual sites at a distance of 10–80 m from each other, and the obtained results were averaged. After drying, the samples were sieved through a set of sieves with the following mesh diameters: 0.1 mm, 0.25 mm, 0.5 mm, 0.8 mm and 1.0 mm. For all samples, the primary grain size indices were determined according to the formulas of Folk and Ward (1957), using in this analysis mainly the average grain diameter Mz and sorting δ.

From the 0.8–1.0 mm fraction, 1–2 teaspoons of sand were taken for mineral composition analysis and processing. The mineral composition was determined in a simplified way, but this was sufficient to assess the impact of the aeolian process on the deposit. The following were separated: less resistant carbonate minerals, more resistant quartz, and other minerals (without marking, with different resistance). It was assumed that the greater the share of quartz grains, the longer the aeolian process lasted (Mycielska-Dowgiałło, Woronko 1998, Woronko 2012). The number of quartz grains counted for testing ranged from 200 to 1000.

The abrasion of quartz grains was examined using the Cailleux (1942) morphoscopic method, as modified by Mycielska-Dowgiałło and Woronko (1998) with the use of an optical microscope. In this method, the following grains are separated: broken C, fresh and angular NU with a degree of rounding of 0.1–0.2 on the Krumbein scale (1941), very well-rounded and shiny EL with a degree of rounding of 0.7–0.9, very well-rounded and mat RM with a degree of rounding of 0.7–0.9, moderately rounded and shiny EM/EL with a degree of rounding of 0.3–0.6 and moderately rounded and mat EM/RM with a degree of rounding of 0.3–0.6.

It was assumed that the measure of the duration of the aeolian process is the ratio of RM and EM/RM grains – if RM grains are more than EM/RM, then the aeolian processes operated for a long time, and vice versa (Mycielska-Dowgiałło, Woronko 1998, Woronko 2012).

Results

Seitan Limania

The site is located on the northern coast of Crete, east of Chania, on the Akrotiri peninsula, in its eastern part (Fig. 1). It is a small beach in a narrow rocky bay located about 4 km east of Chordaki (Fig. 2A). This area is composed of heavily karstified Triassic and Jurassic limestones and dolomites (Mountrakis et al. 2012). The uplift after the 365 AD earthquake was 0–2 m (Table 1), but due to the subsequent sea level rise of 1.25 m, most of the emerging bay floor was again submerged (Mourtzas et al. 2015). The beach consists of strips and patches of deposits of various fractions, mainly gravel or sand. In the north part of the beach, the periodic water flow through a short, very steep gorge causes beach deposits' erosion and the accumulation of fresh material carried up from the gorge.

Three samples of beach deposits were collected, one near the southern cliff of the bay and two

Fig. 2. Research sites on the coast of western Crete: A – Seitan Limania, B – Stavros, C – Balos, D – Elafonisi, E – Orthi Ammos, F – Preveli, G – Matala.

from the middle part of the beach. All represent coarse-grained sands of moderate sorting – the average value of Mz is 0.907 mm, and the sorting δ is 0.80 (Table 2).

The share of quartz grains in the 0.8–1.0 mm fraction is, on average, 11%; carbonate minerals mainly represent the remainder (76%) (Fig. 3). The quartz grains' abrasion is very similar. These are primarily moderately rounded and mat grains EM/RM (47–53%) and fresh and angular grains NU (23–29%). On average, the share of very well-rounded and mat grains RM is 12%, and the same is the percentage share of very well-rounded shiny grains EL (Table 3).

Table 2. Mean grain size (M_z) and sorting (δ).

Site	Name	Mean M_z	Mean sorting δ
		[mm]	[phi]
1	Seitan Limania	0.907	0.80
2	Stavros	0.536	0.59
3	Balos 1	0.287	0.72
	Balos 2	0.907	0.90
	Balos 3	0.426	0.65
	Balos 4	0.277	0.67
	Balos 5	0.496	0.47
4	Elafonisi 1	0.466	1.24
	Elafonisi 2	0.349	0.54
5	Orthi Ammos 1	0.457	1.42
	Orthi Ammos 2	0.227	0.53
6	Preveli	0.722	0.40
7	Matala	0.599	0.59

Table 3. Quartz grain abrasion.

Site	Name	Quartz grain abrasion [%]					
		C	NU	EL	EM/EL	RM	EM/RM
1	Seitan Limania	0	26	12	0	12	50
2	Stavros	–	–	–	–	–	–
3	Balos 1	–	–	–	–	–	–
	Balos 2	0	0	0	0	0	100
	Balos 3	0	0	0	8	14	78
	Balos 4	0	0	0	0	0	100
	Balos 5	0	0	0	0	0	100
4	Elafonisi 1	0	14	0	0	10	76
	Elafonisi 2	0	10	0	3	6	81
5	Orthi Ammos 1	0	16	0	0	2	82
	Orthi Ammos 2	0	18	0	0	4	78
6	Preveli	0	34	0	6	0	60
7	Matala	0	4	0	0	28	68

Stavros

The site is located on the northern coast of Crete in the north-western part of the Akrotiri peninsula, in the town of Stavros on Trachili Bay (Fig. 1). The hills are built of heavily karstified Triassic and Jurassic limestones and dolomites and plate limestones and marbles of the Triassic and Eocene–Oligocene age (Mountrakis et al. 2012). As at the Seitan Limania site, the uplift after the 365 AD earthquake was 0–2 m (Table 1), but the flat bottom that emerged at that time is now submerged by a sea level rise of more than 1 m (Mourtzas et al. 2015).

In the coastal zone, mining activities remain in the Minoan period, as well as in the Middle Ages and later (Tziligkaki 2018). Aeolianite was mined here – a rock formed due to the lithification of deposits accumulated by the wind. In the quarry, there are cylindrical channels with a diameter of several centimetres and a depth of at least 20 cm. According to Epting (1969), these are remnants of the roots and trunks of coastal vegetation that grew in the dunes before being cemented. This interpretation also appears in more recent studies (Keraudren et al. 2000). Some canals have been opened during operation and have a reduced primary depth (Guest-Papamanoli 1989).

Samples were taken in two locations (80 m apart) near the recent shoreline (Fig. 2B). These are coarse-grained, moderately sorted sands. The average Mz value is 0.536 mm, and the sorting δ is 0.59 (Table 2). In the separated fraction of 0.8–1.0 mm, only carbonate minerals with a large share of shells or their fragments were found (Fig. 3). The sediment can be described as carbonate

Table 4. Characteristics of coastal deposits (average values).

Sedimentary environment	Mineral composition			Mean grain size and sorting		Quartz grain abrasion				
	Carbonate minerals	Quartz	Other minerals	Mz	δ	NU	EL	EM/EL	RM	EM/RM
	[%]			[mm]	[phi]	[%]				
High-energy beach	64	13	23	0.437	0.99	15	0	0	6	79
Aeolian	63	11	26	0.447	0.63	5	0	2	4	89
Beach with permanent or periodic rivers	32	25	43	0.743	0.60	21	4	2	14	59

sand. There are no quartz grains; therefore, the abrasion analysis was impossible.

Balos

The site is located on the north-west coast of Crete, on the Gramvousa peninsula, and more precisely on its west coast in the area of the Balos lagoon (Fig. 1). This area is made up of limestone (Triassic–Eocene). The platform between the Gramvousa peninsula and the former island of Kheri Tiganiou is made of Miocene limestone with marl and sandstone intercalations (Mountrakis et al. 2012). As a result of tectonic movements, mainly in 365 AD, the coast was uplifted along active NNE–SSW faults (Caputo et al. 2010). The uplift was 5.5–6.0 m, and according to some sources, even 8 m (Thommeret et al. 1981, Pirazzoli et al. 1996a, b, Stiros 2001, 2010; Table 1). An emerging flattened platform between the island and the peninsula transitions gently into a moderately sloping backshore; beyond is a cliff. Some of the deposits emerging from the sea were strongly cemented as shelly sandstone with limestone fragments (Scheffers, Scheffers 2007). The tsunami, caused either by a sudden uplift in 365 AD or by more recent tectonic events, came from the south and south-west and moved large boulders in the lagoon and on the slopes of the peninsula to a height of more than 8 m, as far as the zone of aeolian sands (Scheffers, Scheffers 2007) (Fig. 2C). The belt of aeolian deposits is oriented from north to south and corresponds to the generally northerly direction of the winds (Pyökäri 1999).

At the Balos site, 15 samples were taken from approximately the following heights above sea level: 1 m (Balos 1), 10 m (Balos 2), 25 m (Balos 3), 35 m (Balos 4) and 45 m (Balos 5). Three samples were taken at a distance of about 10–15 m from each elevation level.

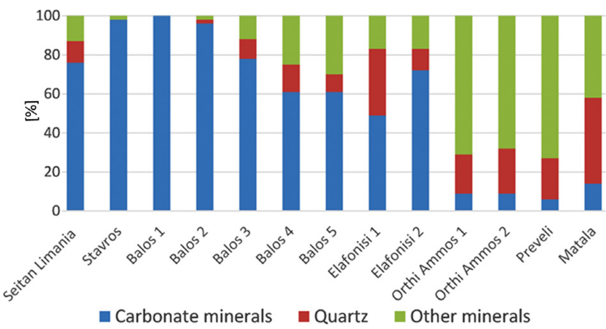

Fig. 3. Mineral composition in the research sites.

Deposits from the Balos 1 site are medium-grained and moderately sorted – the mean value of Mz is 0.287 mm, and sorting δ is 0.72 (Table 2). The 0.8–1.0 mm fraction consists of carbonate minerals with a substantial share of shells, about one-third of which is almost spherical and perfectly polished. No quartz grains were found in any of the samples (Fig. 3).

Moderately sorted coarse-grained deposits occur at the Balos 2 site; the Mz values are 0.853–0.961 mm. On average, 96% of the 0.8–1.0 mm fraction is comprised of carbonate minerals with many shells. A few quartz grains (1–4%) are exclusively EM/RM grains (Table 3).

At the next altitude level (25 m above sea level), in the Balos 3 site, there are medium-grained deposits (mean Mz, 0.426 mm), and moderately sorted (mean δ, 0.65). In the 0.8–1.0 mm fraction, carbonate minerals with shells predominate (average, 78%) (Fig. 3). The share of quartz grains is more significant than in the previous site and amounts to 9–11%. EM/RM grains predominate (average, 76%). RM grains are 14% on average, while EM/EL grains are 8%.

The Balos 4 site also contains medium-grained deposits of moderate sorting (mean values of Mz and δ are 0.277 mm and 0.67, respectively). On average, 61% of the 0.8–1.0 mm fraction is comprised of carbonate minerals (Fig. 3). The shell content is less than in the previous sites. All quartz grains, whose share is in the 11–17% range, are grains of the EM/RM type (Table 3).

At an altitude of about 45 m above sea level in the Balos 5 site, there are medium-grained deposits (Mz, 0.496 mm), and very well-sorted (δ, 0.47). The share of quartz grains averages 9%; all are of the EM/RM type (Table 3). Carbonate minerals still predominate in the deposits, and shells are in smaller amounts than at lower elevations.

Elafonisi

Elafonisi is a small island separated by a shallow lagoon from the south-west coast of Crete (Fig. 1). Its maximum length is 1.5 km, with an average width of 150–300 m. The western part of the island is rocky and rises to a maximum of 39 m above sea level; the rest, the larger part of the area, is low and sandy (beach and dunes) (Fig. 2D). This area is located in the foreland of a mountainous area belonging to the Phyllite-Quartzite unit (Carboniferous–Triassic) (Ott et al. 2022). Earthquakes in 365 AD resulted in an area uplift of about 9 m (Pirazzoli et al. 1996a, b, Stiros 2001, 2010; Table 1). The Krios paleo shoreline lies about 500–800 m east of the island's eastern shore (Ott et al. 2022). The platform between Elafonisi and Crete is vast, flattened and partly under the shallow sea. The natural values of the Elafonisi are protected under Natura 2000.

For the Elafonisi site, four samples were analysed – two from the beach about 5 m from the shoreline and about 100 m from each other (Elafonisi 1) and two from dunes located outside the fenced area with no access (at a distance of about 40 m from each other) (Elafonisi 2). Beach deposits are medium-grained and poorly sorted – the average value of Mz is 0.466 mm, and δ is 1.24. The dune deposits are finer but also medium-grained (Mz is 0.349 mm on average), and better, moderately sorted (δ, 0.54) (Table 2).

In beach deposits, the 0.8–1.0 mm fraction is composed of 49% carbonate minerals with a considerable share of shells, of which about one-fourth is rounded and polished. The percentage of quartz grains is 34% (Fig. 3), with EM/RM grains dominating (76% on average) (Table 3). Very well-rounded and mat RM grains account for 10%, slightly more fresh and angular NU grains (14% on average). There are no other types of grains. In dune deposits, 72% of the 0.8–1.0 mm fraction is comprised of carbonate minerals and shells. The latter is about 40% rounded and polished. The share of quartz grains is three times smaller than in the case of beach deposits and amounts to 11% on average. These are mainly EM/RM grains (81%). NU grains are 10%, RM 6% and EM/EL grains 3% (Table 3).

Orthi Ammos

The site is located on the southern coast of Crete on the Libyan Sea, about 1.5 km east of Frangokastello (Fig. 1). The area is composed of marine deposits, formed as limestones with pebbles, both rounded and angular, and interbedded with sandstones and marls. These deposits belong to the Frangokastello Formation, dating to the Pliocene (van Hinsbergen, Meulenkamp 2006) or the Early Pleistocene (Skourtsos et al. 2007). The formation is partially covered by deposits of Pleistocene–Holocene alluvial cones formed at the south-eastern foothills of the White Mountains (Lefka Ori) (Cheimonas et al. 2016). The area's uplift was approximately 2.0–3.5 m (Price et al. 2002) (Table 1). In contrast to the previously described sites, the backshore is very narrow and turns into a high cliff.

Two deposit samples were taken, one on the beach at approximately 1.5 m above sea level (Orthi Ammos 1) and the other on the windward slope of the dune encroaching on the cliff, at about 10 m above sea level (Orthi Ammos 2) (Fig. 2E). The first is represented by medium-grained sands (Mz, 0.457 mm), poorly sorted (δ, 1.42), and the second by fine-grained sands (Mz, 0.227 mm), moderately sorted (δ, 0.53) (Table 2). In both samples, in the 0.8–1.0 mm fraction, minerals other than carbonates and quartz predominate, accounting for 71% and 68%, respectively (Fig. 3). The share of quartz grains is at the level of 20–23%. EM/RM grains predominate (82% and 78%, respectively). The share of NU grains, amounting to 16% and 18%, is several times higher than that of RM grains (2% and 4%) (Table 3).

Preveli

The site is located on the southern coast of Crete, on the Libyan Sea, at the mouth of the Megas Potamos River flowing from the rocky Preveli Gorge (Figs 1 and 2F). In the lower section, it is formed in low-grade metamorphic units and a Phyllite-Quartzite unit. On the coast, on both sides of the gorge, are seven marine terraces at heights ranging from 14 m to 125 m above sea level. Deposits from the two lowest terraces date back to 45,000–50,000 years BP; Palaeolithic artefacts have been discovered at upper levels (Strasser et al. 2011). The uplift after the 365 AD earthquake was 0–2 m (Table 1), but due to sea level rise, most of the emerged seabed is again under water (Mourtzas et al. 2015).

Samples were taken from the beach, east of the river mouth, approximately 10 m from the shoreline and 20 m apart. Both samples represent coarse sands (average Mz is 0.722 mm). The deposits are very well-sorted (δ, 0.40). In the 0.8–1.0 mm fraction, minerals other than carbonate and quartz predominate in both samples, amounting to 73% on average (Fig. 3). The share of quartz grains is, on average, 21%, mainly EM/RM grains (54–66%). The percentage of fresh and angular NU grains is 34%, and EM/RM grains, 6% (Table 3). A few shells were present in both samples.

Matala

Matala is located in the middle of the southern coast of Crete on Matala Bay, at the foot of the Asterussia Mountains. From the north and south, the bay is bounded by high cliffs (Fig. 2G), and more or less, in the middle of the beach, a river periodically flows out. The area is made up of hard marly limestones (Miocene), and the uplift associated with the 365 AD earthquake was the smallest among those of all sites, less than 1 m (Table 1). In the coastal zone, sea terraces and tidal notches were found to be flooded due to sea level changes during the last 4000 years (Mourtzas, Kolaiti 2020). So, the beach that existed after 365 AD is also underwater. In the walls of the northern cliff, caves are carved into the rock, tombs from Roman times.

The samples were taken in the northern part of the beach about 30 m from the shoreline – one at 40 m from the cliff with caves and the other at 60 m. Both represent coarse sands (Mz averages, 0.599 mm) and are moderately sorted (δ averages, 0.59). In the 0.8–1.0 mm fraction, on average, 14% is comprised of carbonate minerals (without shells). The content of quartz grains is 40–48% (Fig. 3), mostly EM/RM grains (64–72%). Very well-rounded and mat RM grains share 25–31%, and fresh and angular NU grains average 4% (Table 3).

Discussion

The investigated deposits are mostly medium-grained, with average Mz values of 0.277–0.496 mm. In terms of this feature, they do not differ from deposits on other coasts, as mentioned in results of research into modern beach sands in various regions, for example the Pacific, the Gulf of California, the Caribbean and the Gulf of Mexico (Edwards 2001), as well as the Baltic Sea (Tylkowski, Samołyk 2011, Žilinskas et al. 2018). Only dune deposits in Orhi Ammos 2 south of Crete are fine-grained (Mz, 0.227 mm). The most coarse-grained deposits are at the Seitan Limania site on the Akrotiri Peninsula and at the Balos 2 site in the north-west of Crete – in both places, the average value of Mz is 0.907 mm. In the first case, it is associated with the beach's location in a narrow rocky bay, into which coarse material is periodically supplied from a steep gorge. At the Balos 2 site, the coarseness of the deposits is probably due to the proximity of multi-ton boulders, which, according to Scheffers and Scheffers (2007), were brought to the beach by the tsunami after the 365 AD (or later) earthquake. In addition, the site is located near the former shoreline. There are also coarse-grained beach deposits at the mouth of the Preveli Gorge (Mz, 0.722 mm) and on the beaches of Matala (Mz, 0.599 mm) and Stavros (Mz, 0.536 mm).

Most investigated deposits are characterised by moderate sorting with average δ values in the range of 0.53–0.80. The beach deposits at the Elafonisi 1 and Orthi Ammos 1 sites are the least sorted, for which the δ values are 1.24 and 1.42, respectively. In the case of Elafonisi beach, this can be explained by its protrusion into the sea, exposure to stronger winds, and the supply of fresh material. Orthi Ammos beach is very narrow, stretches along the cliff and is also within the range of significant waves. Only beach deposits in the Preveli site (δ, 0.40) and aeolian deposits in the Balos 5 site at an altitude of about 45 m above sea level are very well-sorted.

In terms of mineral composition, the analysed deposits are significantly diversified. In the sites located on the northern and western coasts, the 0.8–1.0 mm fraction is dominated by carbonate minerals, which constitute an average of 77% (range, 46–100%), while on the southern coast, their share is many times lower and ranges from 5% to 16% (average, 9%). However, it does not seem to be a regional, but rather a local, feature. The Pyökäri (1999) study confirms a very high carbonate mineral content at the Stavros and Elafonisi sites. Still, their share is more diverse in other locations on the northern and western coasts, even decreasing to about 10%.

The content of quartz in the investigated deposits is generally low, on average 18%, and in two sites, on the beaches of Stavros and Balos 1, it was not found at all. The most quartz occurs in the sites located on the southern coast of Crete, with the maximum occurring in Matala (44%). Among the sites on the northern and western coasts, where quartz is present, the Elafonisi 2 (dune) stands out with its 34% content. The share of minerals other than carbonates and quartz is the highest in sites on the southern coast, reaching a maximum of 77% (Preveli).

The high share of less resistant carbonate minerals, with a small amount of more resistant quartz grains, means that most investigated deposits are relatively young and were briefly in the range of aeolian processes.

Both beach and dune deposits are dominated by moderately rounded and mat grains EM/RM with a share of 47–100%, on average 79%. The content of very well-rounded and mat grains RM is the highest in the Matala site (on average 28%); in four places, these grains do not occur at all, while in the remaining sites, their share is, on average, 8%. The higher content of EM/RM grains in relation to RM grains is considered an indicator of short-term aeolian transport (Mycielska-Dowgiałło, Woronko 1998, Woronko 2012). In the studied sites, this predominance is multiple, and thus it can be concluded that the deposits representing them have been in the aeolian environment for a very short time. This is indirectly confirmed by their young age, as most of the studied deposits emerged from the sea due to a several-metre uplift of western Crete resulting from an earthquake less than 1660 years ago (Thommeret et al. 1981, Pirazzoli et al. 1996a, b, Stiros 2001). The research conducted by Mourtzas and Kolaiti (2020) shows that in Matala Bay, sea level changes did not cover the zone where the Matala site was established. It means that beach deposits found here have been in the terrestrial environment longer than on other beaches studied. This probably explains the better abrasion of quartz grains, expressed by the highest share of RM grains among all sites. The research results of Pyökäri (1999) indicate that in western Crete, very well-rounded and rounded grains are relatively few – in the group of non-carbonate grains, they constitute an average of 4%.

A feature of the studied deposits is the negligible content of EL and EM/EL grains, characteristic of, among others, the high-energy beach environment (Krinsley, Doornkamp 1973, Lindé, Mycielska-Dowgiałło 1980, Mycielska-Dowgiałło, Woronko 1998). EL grains were found only in the Seitan Limania site (average, 12%), while a few percent shares of EM/EL grains were found in the Preveli and Balos 3 and 4 sites (Table 3). In the beach environment, grains are constantly in motion, and thus they travel a long way, often in high-energy conditions (Krinsley, Doornkamp 1973, Mycielska-Dowgiałło 1988). The collision between the grains during waves and tides results in mechanical abrasion, but in warm climate zones, the grains are also subjected to chemical etching (Setlow 1978). As a result of these processes, the effect of matting of the whole grains can be created, which is already visible under the optical microscope (Goździk, Mycielska-Dowgiałło 1982, Mycielska-Dowgiałło 1988). It cannot be ruled out that a certain part of the grains considered under the optical microscope as EM/RM grains, would, in an examination under the scanning electron microscope (SEM), be regarded as grains that are dull due to chemical etching. Nevertheless, the study of the surface microtexture of quartz grains from Japanese beach deposits using SEM conducted by Itamiya et al. (2019) showed that in high-energy beach conditions, mechanical features are more often recorded on the quartz surface than chemical features.

The investigated deposits are diversified in terms of the content of fresh and angular grains NU. They were not found in any of the five sites on Balos, and in the remaining sites, their share in the 0.8–1.0 mm fraction is, on average, 17%. The largest share of NU grains is found in beach deposits at the mouth of the Preveli Gorge (34%) and in the rocky bay of Seitan Limania (26%). The analysis of diagrams from the work of Pyökäri (1999) shows that in western Crete, among non-carbonate grains (quartz and others), very angular and angular grains account for about 50% on average. Individual sites, however, are very diverse in this respect. The extreme values refer to two areas analysed in this study: for Stavros, they amount to several percent (in this study, no quartz grains were found in this site), and for Elafonisi, they oscillate around 80% (in this study, several times less, 17%). The above discrepancies can be partly explained by the high dynamics of processes in the coastal zone, multiple redeposition of deposits, and the variability of their textural features. It is worth quoting the results of research by Garzanti et al. (2015), who found that sand transported by coastal currents along the south-west coast of Africa remains angular for hundreds of kilometres and becomes rounded relatively quickly when it reaches the Namib Desert.

Scheffers and Scheffers (2007) found compelling evidence of a tsunami covering the Balos area, which rapidly remodelled the geomorphology and lithology of the coastal zone. However, without performing a study under a scanning microscope, it is difficult to determine whether this has been recorded in the texture of the quartz grains. The results of the research conducted by Costa et al. (2012) on the microtexture of quartz grains transported by the tsunami indicate the lack of any specific features in grain processing, but the share of fresh surfaces and traces of impact increases. According to Bellanova et al. (2016), who studied two tsunami deposits in Tirúa, Chile, there are no statistically significant differences between tsunami, beach, dune and river deposits, and microtextural analysis of quartz grains may not be a suitable method for identifying tsunami deposits.

When generalising the results, more or less clear differences can be seen between the deposits of the studied sedimentary environments. Deposits from beaches fed by alluvial rivers (permanent or periodic) stand out. Compared to aeolian deposits and beach deposits supplied only from the sea, they contain, on average, twice as much quartz (25%) and twice as much carbonate minerals (32%). In addition, they are characterised by the absence or a small share of shells, coarser grain (Mz is 0.743 mm on average) and a large share of fresh and angular NU grains (on average 21%). In turn, deposits from beaches without tributaries are characterised by a high content of carbonate minerals and well-rounded and polished shells. Most quartz grains are moderately rounded and mat EM/RM (average, 79%). Deposits from these beaches were the source of material for dunes and aeolian cover sands. This is evidenced not only by the mutual geomorphological location but also by the similar mineral composition and the presence of shells. On the other hand, the record of aeolian abrasion is a higher share of EM/RM grains (on average 89%).

The investigated deposits are young and generally characterised by poor and moderate quartz grain abrasion. It is not an isolated situation that the exposure of the deposits to relatively short wind activity (in this case for about 1500 years) only results in some aeolian retouching of the grains. One can cite the example of much older aeolian deposits in the Barguzin Basin in Transbaikal, 3000–4000 years old (Wyrkin 1998), with very poor abrasion. As research by Ovchinnikov et al. (2002) indicates, the share of moderately rounded and mat grains is, on average, 91.5%, and similar to their share in the bedrock deposits (90.9%).

Conclusions

Coastal deposits in western Crete occur in areas with a varied scale of uplift, lithology and coastal morphology. To determine the degree of aeolian abrasion of deposits that emerged from the sea after the 365 AD earthquake, attention was focussed on deposits from the backshore and from coastal dunes (deposits that were at least periodically exposed to wind transport). Deposits representing three sedimentary environments were examined – high-energy beach, aeolian, and beach with permanent or periodic fluvial supply. As a result, the following have been established:

1. Beach deposits are characterised by a high content of carbonate minerals (average, 64%; maximum, 100%) and well-rounded and polished shells. These are medium-grained sands (Mz is 0.437 mm on average) with moderate or poor sorting (δ ranges from 0.59 to 1.42). The share of quartz is small, ranging from 0% to 34%, with an average of 13%. No EL and EM/EL grains were found, which are characteristic, among others, of the high-energy beach environment. Moderately rounded and mat EM/RM grains predominate (average, 79%). It means the beach deposits (from the backshore) have been subjected to aeolian abrasion.
2. Aeolian deposits build coastal dunes and fields of blown sands. The source of the material for them was beach deposits, which is indicated by both the geomorphological location and similar mineral composition. Aeolian sands contain almost the same amount of carbonate minerals (on average 63%; maximum, 96%) and shells, including well-round-

ed and polished ones. The share of quartz is small (average, 11%; maximum, 23%). Aeolian sands are medium-grained (Mz is 0.447 mm on average) and well to moderately sorted (δ is from 0.47 to 0.90), which is better compared with the situation characterising beach deposits. Most quartz grains are moderately rounded and mat – the proportion of EM/RM grains is, on average, 89%, with a maximum of 100%. The larger average share of grains of this type is a measure of the increase in the degree of aeolisation of deposits.

3. Deposits from the beach with permanent or periodic fluvial supply differ from the above-mentioned deposits. First of all, they contain, on average, twice as much quartz (25%) and two times less carbonate minerals (32%), and much more minerals other than quartz and carbonates (43% on average; maximum, 73%). These deposits are also characterised by the absence or a small proportion of shells; they are also distinguished by coarser grains (Mz is, on average, 0.743 mm). Regarding aeolian abrasion, a large percentage of fresh and angular NU grains (average, 21%) and a smaller share of EM/RM grains than in aeolian and beach deposits are noteworthy, by 30% and 20% on average, respectively. It means that the supply of fluvial material significantly impacted these deposits' grain size and abrasion characteristics.
4. The mineral composition of the studied coastal deposits depends on the local geology. Generally, on the northern and western coasts built of carbonate rocks, carbonate minerals dominate in the 0.8–1.0 mm fraction (77% on average). On the southern coasts made of metamorphic, phyllite-quartzite rocks, their share is many times smaller (average, 9%), while the percentage of quartz is the largest and amounts to a maximum of 44%, and the average quartz content in all examined coastal deposits is 18%. These data are essential because a large share of less resistant carbonate minerals, with a small amount of more resistant quartz grains, means that most of the examined deposits are relatively young and were briefly within the range of aeolian processes.
5. In general, the degree of aeolisation of coastal deposits can be described as weak, at most moderate. These deposits are dominated by moderately rounded and mat grains EM/RM (average, 79%). The very well-rounded and mat RM grains content is low (average, 18%). The higher content of EM/RM grains in relation to RM grains proves a short-term aeolian transport. The predominance is multiple, and thus the deposits stayed in the aeolian environment for a short time, indirectly confirming their young age. Most of the examined deposits emerged from the sea owing to the fact that, after an earthquake less than 1660 years ago, western Crete underwent an uplift by a few metres, and such deposits have been periodically affected by aeolian processes since then.

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