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Provenance-related characteristics of beach sediments around the island of Menorca, Balearic Islands (western Mediterranean)

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Abstract The island of Menorca, one of the Balearic Islands (Spain) located in the western Mediterranean, is characterised by a contrasting geology and landscape with two major geographic domains: (1) a southern region called Migjorn, comprised of Late Miocene calcarenites and limestones, and (2) a northern region known as Tramuntana, which is composed of folded and faulted Palaeozoic, Mesozoic and Tertiary (Oligocene) siliceous and calcareous rocks. Both domains are lined by numerous pocket beaches exhibiting a high variety of surficial sediment assemblages. Grain-size and compositional analyses revealed that cliff erosion and nearshore *Posidonia oceanica* meadows are the main sources of sediments consisting mostly of medium- to coarse-grained carbonate sands of marine biogenic origin, with variable amounts of terrigenous rock fragments and quartz. Based on distinctly different contributions of bioclastic material, biogenic carbonates and quartz, 320 sediment samples from 64 beaches were grouped into different facies associations dominated by either (1) biogenic sands, (2) biogenic sands with terrigenous contributions or (3) terrigenous sands with quartz. Nevertheless, there is a marked regional variability in sediment texture and composition. Thus, variable mixtures of carbonate and siliciclastic sediments characterise the beaches of the northern region, whereas the beaches of the southern region are composed mostly of carbonate sands of marine biogenic origin. An exception is the central sector of the south coast, which is enriched in quartz sand (~10 %); this can be related to outcrops of quartz-rich basement rock and also to rocks exposed in some northern drainage basins captured by southern streams since the Plio-Quaternary.

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Introduction

Since the 1960s, coastal scientists have understood beaches as dynamic sedimentary systems, which require a number of boundary conditions and external inputs in the form of waves and sediments, and accommodation space (e.g. Ibbeken and Schleyer 1991; Short 1999). Sufficient sediment supply is an essential requirement for the maintenance of beaches, the sediment being moved by waves and nearshore currents over suitable substrates to a final accommodation area (Woodroffe 2003). In terms of system theory, the volume of sediment composing and moving through a beach system defines the sediment budget, which is equal to the balance between input and losses of sediment over a given period of time (Carter 1988).

The main sediment inputs to beach systems are derived from (1) terrigenous sources such as fluvial supply and cliff erosion, and (2) marine sources such as seabed erosion and marine biogenic production. In addition, the sediment supplied to a beach can be laterally dispersed by alongshore currents and littoral drift. Sediment losses from beaches occur mostly during high-energy events (storms) when wave- and wind-induced onshore, offshore and alongshore currents permanently remove sediment from a beach, as well as during onshore wind events, which transport sediment landwards into temporary or permanent coastal dune repositories. As a consequence, beach sediment budgets typically fluctuate over a range of temporal scales. However, to maintain a beach in the long run, the sediment budget must be positive or at least balanced, as negative budgets ultimately result in partial or complete beach erosion (Komar 1996).

The provenance of sediments in beach sediment budgets is controlled by both natural conditions (e.g. lithology, relief, climate, energy conditions) and anthropogenic influences (e.g. constructional interference, sand mining, dumping; e.g. Johnson 1993). Thus, the mineralogical composition and grain-size spectra of beach sand are at least partially dependent on the lithology of the source rocks, the duration of transport from source to sink, the frequency and intensity of the deposition/erosion cycles of beaches, and the degree of local biogenic sediment production. Therefore, factors such as climate, geological history, tectonic processes and lithological aspects, as well as the local wave climate, play important roles in the physical processes determining the composition of beach material (e.g. Ibbeken and Schleyer 1991; Carranza-Edwards et al. 1998; Sanderson and Eliot 1999).

Despite the wealth of research on beach sediment sources through the analysis of mineral composition (e.g. Komar and Wang 1984; Clemens and Komar 1988), comparable work on carbonate-dominated sand beaches is relatively scarce (cf. Komar 1998). Numerous studies on beach sedimentation have dealt either with siliciclastic sands (e.g. Bryant 1982; Davis 1985; Sagga 1992; Guillén and Hoekstra 1996; Guillén and Palanques 1996; Carranza-Edwards et al. 1998; Anthony and Héquette 2007) or, in tropical environments, with calcareous sands of marine origin (e.g. Kench 1997; Beanish and Jones 2002; Smith and Cheung 2002; Kennedy et al. 2002; Hewins and Perry 2006). Very few studies, by contrast, have focused on temperate and cool-water carbonate sediments (e.g. Lees and Buller 1972; Hansom and Angus 2001; Fornós and Ahr 2006; Brandano and Civitelli 2007) or calcareous beach sands in general (e.g. Jaume and Fornós 1992; De Falco et al. 2003). Bioclastic carbonate sands are commonly composed of skeletal fragments of corals, coralline and green algae, foraminifers and molluscs. The shapes of bioclastic sand grains are highly variable in comparison to the rounded, uniform quartz sands composing terrigenous beach sediments. The nature and texture of biogenic carbonate grains, in contrast to the abundance of terrigenous or quartz grains, may therefore be useful in identifying the contribution from various terrigenous and marine sources.

The present study is based on the analyses of a large number of surficial beach and upper shoreface sediment samples from around the island of Menorca in the western Mediterranean. Because of the relatively small size of the island and its contrasting geology, Menorca represents a good field laboratory for assessing the interaction between carbonate and terrigenous/siliciclastic sedimentation, and the related controls on beach sediment sources and patterns of beach facies evolution. Against this background, specific questions addressed in this paper include (1) what types of sediments characterise Menorca's beaches and how are these distributed along the coast, (2) what are the sources for different sediment types and (3) how does the distribution of the sediments reflect the geomorphic evolution of Menorca?

Regional setting

Geology and physiography

The island of Menorca is located at the north-easternmost end of the Balearic Promontory in the western Mediterranean (Fig. 1a), and can be subdivided into two physiographic regions: the Migjorn, or southern region, comprising almost horizontally bedded Late Miocene calcarenites and limestones (Obrador et al. 1983; Pomar et al. 2002), and the Tramuntana, or northern region, characterised by folded and faulted Palaeozoic, Mesozoic and Tertiary (Oligocene) strata. The two structurally distinct regions are separated by a major normal fault of Late Miocene age that dips towards the SSW with an ESE–WNW orientation (Fig. 1b). The Tramuntana constitutes an uplifted block, whereas the Migjorn represents a downfaulted block.

The geological structure of the island thus broadly consists of an Early Miocene imbricate thrust system (outcropping in the Tramuntana), which is unconformably overlain by Late Miocene sediments forming the Migjorn (Bourrouilh 1983; Roca 1992). The thrust sheets comprise Palaeozoic, Mesozoic and Tertiary (Oligocene) sediments, the low-angle E–SE-dipping thrust faults (N–S or NNW–SSE aligned) being rooted in Silurian shales and Late Triassic marls (Bourrouilh 1983). Late Miocene sedimentation in the Migjorn was controlled by a several kilometres long, NNE–SSW-oriented normal fault located in the Tramuntana. This fault was subsequently reactivated as a reversed fault in Pliocene times, causing the Late Miocene sediments of the southern region to be upwarped and thereby generating a gentle anticline that constitutes the most characteristic physiographic feature of the Migjorn (Gelabert et al. 2005). The Tramuntana is higher in elevation (with El Toro forming the highest peak of the island at 361 m above mean sea level), whereas the Migjorn has a more rugged topography caused by

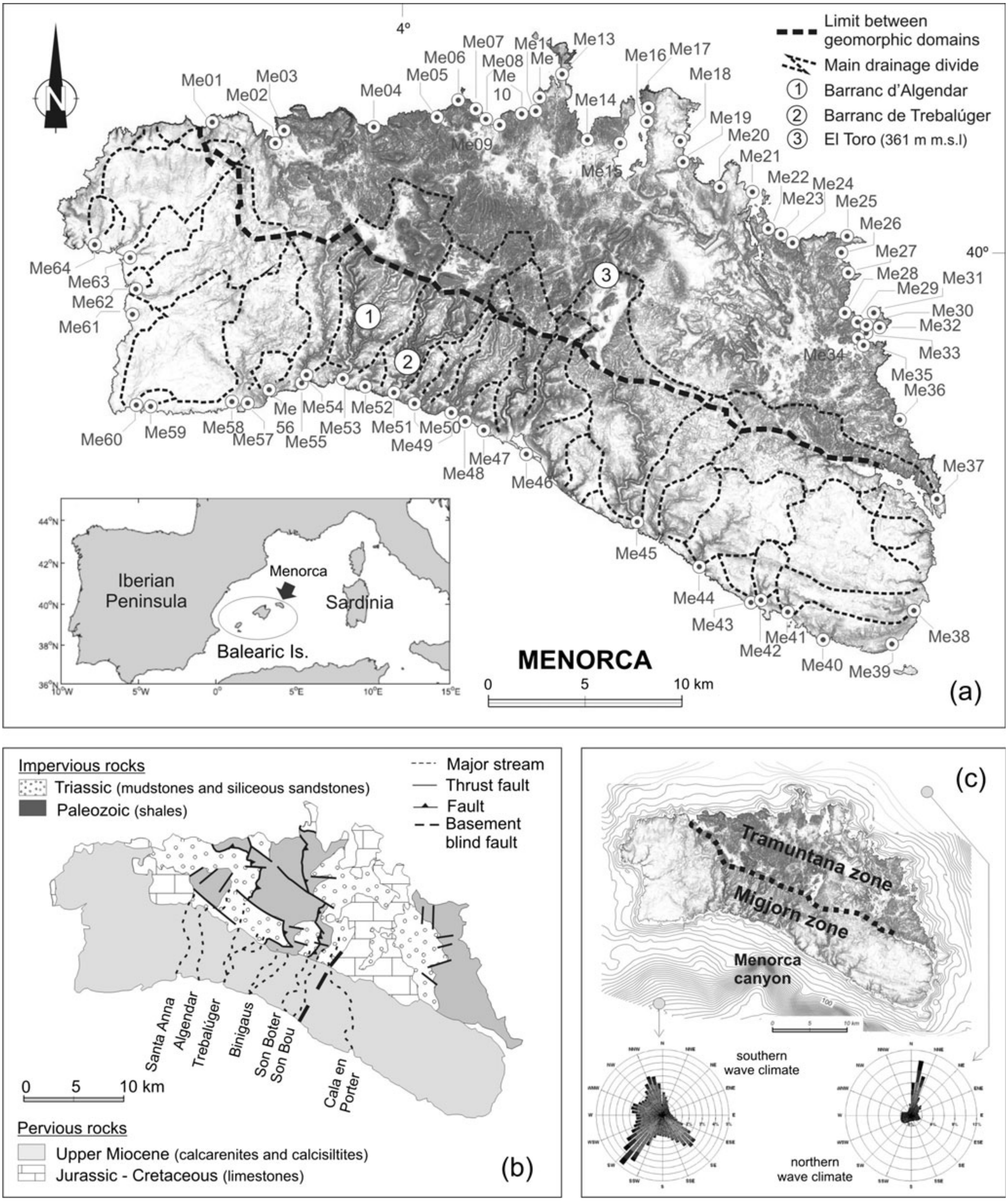

Fig. 1 **a** Slope terrain model of Menorca island: *dotted circles* sediment-sampling stations, *encircled numbers* locations referred to in the main text. **b** Simplified geology of the island. **c** Local bathymetry: *wave rose diagrams* wave climates of the north and south coasts, together with the major geomorphic regions

elevation differences between the drainage divides and the streambeds, the latter occupying deep fluvio-karstic canyons that are separated by relatively flat elevated areas. Notably, the streams in the central sector of the Migjorn are more deeply incised or entrenched than those in more peripheral areas (Gelabert et al. 2005).

Hydrology and climatology

Most streams are ephemeral, and only the larger ones (Algendar and Trebalúger, Fig. 1) of the central sector of the island are continuous, although these exhibit very low mean annual discharges (<0.003 $m^3 s^{-1}$) near their mouths resulting largely from the draining of Migjorn karst aquifers (Gelabert et al. 2004). Important to note here is that the headwaters of some of these streams lie beyond the Migjorn within the Tramuntana, the rocks of which are more impervious than those of the Migjorn. As a consequence, the streambeds of the latter region lack typical fluvial deposits; the river loads in the higher-discharge wet season mainly comprise decalcified clays with some sand but without any coarser material (Segura et al. 2007).

Menorca has a Mediterranean climate with a mean annual rainfall of 550–650 mm, whereby winter is the wettest season. Rainfall is generally higher in the central, most elevated part of the island, and particularly low along the south coast. The mean annual temperature is 16.5–17 °C, the weather being slightly warmer on the eastern and southern sides of the island (Pons et al. 2003).

The marine environment

The so-called Balearic Platform is an isolated platform bounded by oceanic basins that reach more than 2,000 m in depth. It is separated into a southern and a northern island complex, the islands of Mallorca and Menorca belonging to the latter. The platform forms a distally steepening ramp having an average width of 15 km and an average initial slope of 10 $m km^{-1}$ between the shoreline and water depths of about 150–200 m (Fig. 1c). From there onwards (basinwards), the average slope increases to about 80 m km^{-1}. A large submarine canyon marks the southern flank of Menorca (Alonso et al. 1988; Acosta et al. 2003). The surrounding Balearic Sea is a temperate oligotrophic marine environment characterised by exceptionally clear water.

Maximum deep-water wave heights rarely exceed 8 m, being associated with storms that are driven by strong NE winds (up to 40 $m s^{-1}$) with a fetch originating in the Ligurian Sea (Fig. 1c). The north-western and central parts of the Balearic Sea are exposed to northerly winds (the Mistral) for the major part of the year, while the eastern part is characterised by greater seasonal variability (Cañellas et al. 2007). Forcing by tides is almost negligible in the Mediterranean, the spring tidal range being less than 0.25 m, although changes in atmospheric pressure and wind stress can account for considerable fluctuations in coastal water levels (Gómez-Pujol et al. 2007). The absence of significant tides restricts beach morphodynamics to wave action and coastal current influences, especially during severe weather episodes when wave-related processes are enhanced.

Materials and methods

Sediment samples were collected from 64 beaches in 1999–2000 as part of a geomorphological survey conducted by the Balearic Islands University and the Menorcan Coastal Management Services (see data report by Gómez-Pujol et al. 2000). At least five representative samples were acquired from the uppermost shoreface (1–1.5 m depth) in each case, resulting in a total of 320 sediment samples. Sampling was conducted by dragging an oval metallic frame attached to a plastic bag a short distance across the beach; sediment penetration was 2–4 cm, and sample masses ranged from 200 to 500 g. In the laboratory the samples were soaked in fresh water for 4 h and, after careful draining, treated for 24 h with a 5 % sodium hypochlorite solution to eliminate organic material. The treated samples were then oven dried at 105 °C for 24 h and subsequently split into subsamples for sieve analysis.

Grain-size analyses were carried out by dry sieving using a series of sieves ranging in mesh size from –2 to 4 phi at half-phi intervals. In each case, about 200 g of sediment was shaken for 15 minutes, the sieve fractions being thereafter weighed and stored in separate bags. The calculation of textural grain-size parameters followed the percentile statistical method proposed by Folk and Ward (1957) using the GRADISTAT© software (Blott and Pye 2001). In order to assess the precision of sieving, ten random samples were sieved five times. The relative standard deviation was found to be only 0.23 % and 0.91 % for mean grain size and sorting respectively. In addition, at least four subsamples of ten different samples were compared to assess how representative the subsampling procedure was. Again the relative standard deviation was found to be very low, amounting to 1.6 % and 1 % for mean grain size and sorting respectively. In accordance with these errors tests, one subsample per sample was sieved at least three times. If the coefficient of variation was larger than 3 %, the analysis was repeated on a new subsample until the coefficient of variation was lower than 3 %.

Sediment composition was established by point counting 100 grains from each of the size fractions under a binocular microscope. Grains were classified into 14 categories, including quartz, lithoclasts, foraminifers, bivalves, gastropods, bryozoans, free-living coralline algae (red algae), fragments of crustose red algae, echinoids, echinoid plates, serpulids, ostracods, sponge spicules and indeterminate biogenic grains. In the present case, lithoclasts correspond to rock fragments, irrespective of these being of carbonate or siliciclastic origin. The weight percentages of the components of the individual fractions were subsequently summed and expressed as percentages of the total subsample (Kench 1997).

Facies analysis was performed on the basis of mineral composition, grain size, and sorting. Statistical analyses were by means of the SPSS® package, involving hierarchical cluster analysis to identify correlations between sediment samples. First, the nearest neighbour method was applied to eliminate outliers, and then the final cluster analysis was made using the Ward methods with Euclidic distance intervals as proposed by Halfar et al. (2001). Once sediment samples were grouped, composition and grain-size attributes were explored in order to identify facies associations, and then synthetic descriptive variables (i.e. average mean grain size, mean composition percentages) were computed.

Results

Sediment texture and composition

The grain-size analyses reveal that the sediments of the uppermost shoreface around Menorca are characterised by moderately sorted medium to coarse sands (see raw data in Table 1 of the online electronic supplementary material for this article). The mean grain size of all samples combined is 1.28±0.81 phi, the coarsest sediment (station Me07) having a mean grain size of –0.16±0.02 phi in one of the most exposed sectors of the north coast. The finest sediment (station Me63) has a mean grain size of 3.87±0.04 phi, being associated with a small protected pocket beach on the southeast coast of the island.

According to the analyses, 95.1 % of Menorca beach sediments are composed of sand, 4 % of gravel, and 0.9 % of mud (silt and clay). Overall, the beach sediments are moderately sorted (35.9 % of all locations) or moderately well sorted (32.8 %), the sorting generally decreasing as the proportion of bioclasts in the sediment increases. Thus, 78.4 % of the sediment grains consist of fragments of crustose and free-living coralline algae (red algae), bryozoans, foraminifers, bivalves, gastropods and other skeletal carbonate grains. The relative proportion of these components ranges from 9–99.4 %, most of the grains having irregular and/or subangular shapes. Lithoclasts (27 %) and quartz grains (6.1 %) form subordinate components in comparison to the skeletal carbonate grains.

The beach sediments of the Migjorn coast (stations Me38 to Me64) are on average finer-grained (1.51 phi) than those of the Tramuntana coast, with mean grain sizes ranging from 3.87±0.22 to 0.02±0.01 phi (Table 1). Although more than 50 % of the beaches along the south coast are medium-grained, the distribution of mean grain sizes shows a distinct regional pattern. Thus, the beaches located in the central sector of the Migjorn coast are generally finer-grained than the beaches to the southeast and southwest. In fact, stations Me46, Me54, Me57, Me58 and Me63 are characterised by fine to very fine sands (mean grain sizes <2 phi). Overall, the sediment is moderately sorted (0.82 phi), 40.7 % being moderately well sorted and 55.6 % evenly split between moderately sorted and very poorly sorted.

In terms of composition, the sediments along the Migjorn coast are mixtures of biogenic carbonate grains with small contributions of quartz and lithoclasts. Of this, indeterminate biogenic grains contribute 56.9 %, red algae 11 %, foraminifers 4.7 %, and mollusc fragments (bivalves and gastropods) 9.2 %, while quartz and lithoclasts together on average contribute only 5 %. An exception are a group of beaches in the central section of the south coast (stations Me47 to Me58), where quartz grains may be enriched to >10 %.

In contrast to the Migjorn coast, the sediments of the Tramuntana coast (from Me01 to Me37, Fig. 1) are on average somewhat coarser (Table 1), mean grain sizes ranging from fine (2.92±0.22 phi at station Me16) to very coarse (–0.16±0.01 phi at station Me07). Although the northern

Table 1 Descriptive grain size and textural parameters for the Migjorn and Tramuntana geomorphic regions

	Grain size (phi)	Sorting (phi)	Skewness	Kurtosis	Gravel (%)	Sand (%)	Mud (%)
Tramuntana region							
Mean	1.19±0.79	0.83±0.24	–0.14	1.01	5.1	94.6	0.3
Min.	2.92	0.44	–0.45	0.74	0.0	79.0	0.0
Max.	–0.16	1.34	0.24	1.66	21.0	100.0	2.5
Migjorn region							
Mean	1.51±0.76	0.82±0.30	–0.08	1.04	2.5	95.7	1.8
Min.	3.87	0.44	–0.31	0.79	0.0	53.8	0.0
Max.	0.02	1.59	0.24	1.50	15.8	100.0	44.4

beaches are generally dominated by sand (94.6 % of the samples), gravel locally contributes as much as 21 % at very exposed locations. Fine sands are typical for recessed and sheltered beaches as, for example, at stations Me10 and Me16. Nearly one third of the Tramuntana beaches (32.4 %) are composed of moderately well sorted sediment. Well sorted beach sediments (e.g. at stations Me02, Me09 and Me 24) are found along the northwest coast, which is exposed to powerful north-westerly gales. By contrast, most of the poorly and moderately sorted sediments occur along the northeast coast or within coves of small bays sheltered from major gales (e.g. stations Me14, Me21 and Me37).

The sediments from the north coast comprise mixtures of terrigenous and biogenic sediments, indeterminate biogenic grains on average contributing 49 % to the total sediment. Lithoclasts (fragments of calcareous and non-calcareous origin) and quartz grains on average contribute 25.4 % and 2.9 % respectively, maximum contributions reaching 71.2 % and 27.3 % (Table 2). The remaining components are bivalves (5.2 %), foraminifers (3.4 %) and red algae (5.9 %).

Sedimentary facies

On the basis of the statistical analyses, three major sedimentary facies were identified (Fig. 2). Two of these were further subdivided into subfacies due to distinctly different contributions of skeletal carbonate or quartz components (Table 3).

Facies F1: biogenic sands

This facies consists of medium sand with a very high abundance of biogenic fragments. It has been subdivided into two subfacies on the basis of the abundance of skeletal carbonate grains.

Subfacies F1a: medium biogenic sands with foraminifers: this subfacies consists of moderately sorted medium sand (97.6 %) comprising a mixture of indeterminate skeletal grains (59.7 %), benthic and planktonic foraminifers (12 %), fragments of red algae (6.6 %), bivalves (4.9 %), bryozoans (3.9 %) and gastropods (3.6 %). Quartz and lithoclasts together contribute 6 %. This subfacies occurs both along the Migjorn and the Tramuntana coasts (Fig. 3).

Subfacies F1b: medium biogenic sands with bivalves and red algae: this subfacies is largely restricted to the south coast of the island (Fig. 3), and consists mainly of moderately sorted medium to coarse sand. The sediment contains up to 70 % carbonate grains, among which red algae (33.2 %) and bivalves (10.2 %) form the dominant components. Lithoclasts contribute 6 %, whereas quartz grains occur in traces only.

Facies F2: biogenic sands with terrigenous contributions

This facies consists of coarse to medium sand and, although the biogenic component is dominant, terrigenous grains, including lithoclasts (both carbonate and siliciclastic) and quartz grains, also make important contributions to the bulk sediment. On the basis of the mean grain size and the abundance of skeletal carbonate and quartz grains, this facies has been subdivided into three subfacies.

Subfacies F2a: coarse biogenic sands with terrigenous contributions: this subfacies consists of moderately sorted coarse sand. The sediment consists of a mixture of indeterminate skeletal fragments (64.5 %) and lithoclasts (23 %). Other components are bivalves (2 %), gastropods (2.3 %), quartz (2.2 %), and fragments of red algae (1.6 %). This subfacies is restricted to the Tramuntana coast (Fig. 4).

Subfacies F2b: medium biogenic sands with terrigenous contributions: moderately sorted medium sands (96.5 %) dominate this subfacies. The composition shows a relatively high abundance of indeterminate skeletal grains (33.3 %) and lithoclasts (23 %), while bivalves (6 %), fragments of crustose red algae (6 %), foraminifers (4.7 %), gastropods (3.6 %) and quartz

Table 2 Sediment composition (both bio- and lithoclasts) for the Migjorn and Tramuntana geomorphic regions (all values in %)[a]

	Quartz	Litho.	Forams	Bivalves	Gastrop.	Bryoz.	Red al.	Echin.	Serp.	Ostrac.	Sponge	Indet.	Others
Tramuntana domain													
Mean	2.9	25.4	3.4	5.2	2.4	2.2	5.9	1.6	0.4	0.4	0.5	49.3	0.4
Min.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.0	0.0
Max.	27.3	71.2	24.1	17.0	15.1	20.5	31.8	6.4	4.4	2.7	11.6	76.7	6.1
Migjorn domain													
Mean	5.8	5.3	4.7	5.1	4.1	2.7	11.0	2.7	0.7	0.4	0.2	56.9	0.5
Min.	0.0	0.0	0.1	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	17.8	0.0
Max.	19.0	21.4	19.4	21.9	11.4	12.5	41.0	7.4	7.0	2.3	1.8	81.6	4.2

[a] Quartz, lithoclasts, foraminifers, bivalves, gastropods, bryozoans, red algae, echinoids, serpulids, ostracods, sponge spicules, indeterminate, others

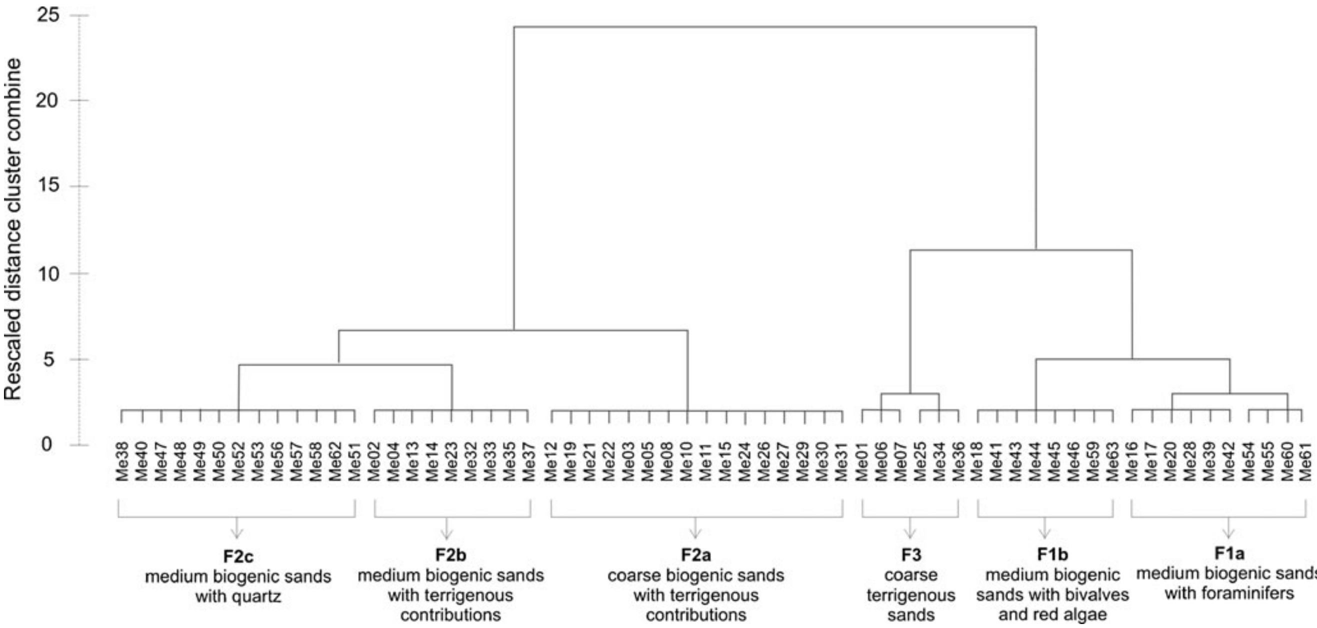

Fig. 2 Results of hierarchical cluster analysis based on sediment composition and grain size (see main text for more information)

(3.7 %) form subordinate components. This subfacies is found at several distinct physiographic locations ranging from sheltered coves to beaches directly exposed to the northerly gales (Fig. 4).

Subfacies F2c: medium biogenic sands with quartz: this subfacies consists of moderately sorted medium sands (98.2 %) and is restricted to the Migjorn coast (Fig. 4). Indeterminate skeletal grains reach 54 %, a characteristic feature being the relatively high abundance of quartz grains in comparison to other beaches in similar environmental and morphological settings. Thus, quartz grains generally contribute up to 6 % to the sediment, and in some cases 10 % and more. Samples containing >10 % quartz occur in the central coastal sector of the Migjorn (from Me47 to Me58).

Facies F3: coarse to very coarse terrigenous sands

This facies consists of moderately well sorted coarse to very coarse sands, including up to 14 % gravel. The terrigenous component consists of lithoclasts, mainly detached from cliffs, which on average contribute 56.6 % to the sediment. Biogenic carbonate grains account for nearly 25 % of the bulk sediment, whereas bivalve fragments make up 6.2 %. This facies is only found on beaches along the north coast that are directly exposed to northerly waves and/or backed by vertical cliffs (Fig. 5).

Discussion

The uppermost shoreface sediments around Menorca show marked variations in terms of composition and texture, both within and between the Migjorn and Tramuntana regions. The rugged coast, with its numerous isolated sedimentary cells separated by rocky promontories and capes, accentuates this variability. Along Menorca's perimeter, there is only one straight coastal sector located on the south coast between Binigaus (Me49) and Son Bou (Me47) where several beaches are interconnected by alongshore transport processes (Gómez-Pujol et al. 2004).

Along the north coast of Menorca, the sediments are coarse and enriched in lithoclasts, whereas along the south coast the sediments consist of medium sands containing abundant biogenic grains (mainly bivalve, gastropod, red algae and indeterminate biogenic fragments). This differentiation is borne out by a cluster analysis based on texture and composition, which has distinguished three major facies. Two of these have been further subdivided into overall five subfacies, the distribution of which shows clear spatial patterns. Thus, the Migjorn coast is best represented by subfacies F1a (biogenic sands with foraminifers) and F1b (medium sands comprising mainly bivalves and crustose red algae). These subfacies are only found very locally at sheltered locations along the Tramuntana coast. As terrigenous inputs are poor due to the absence of effective stream discharges, the high abundance of skeletal grains (bivalves, gastropods, foraminifers, red algae fragments, among others) highlights the dominating role of Recent marine sedimentation. Even the high contribution of indeterminate biogenic grains can be traced to the reworking of sub-Recent biogenic material and the erosion of coastal cliffs. As in the case of the neighbouring island of Mallorca (Jaume and Fornós 1992), which has a similar geology and depositional character, it can be interpreted that

Table 3 Sedimentary facies characteristics of Menorca surf zone sediments

Facies	Subfacies	Beaches	$CaCO_3$ (%)	Gravel (%)	Sand (%)	Mud (%)	Main components (mean %)
F1	F1a	Me16, Me17, Me20, Me28, Me39, Me42, Me54, Me55, Me60, Me61	74.7 to 96.4	0 to 8.6	91.1 to 100	0 to 2	Indeterminate carbonate grains (59.7 %), foraminifers (12 %), red algae (6.6 %), bivalves (4.9 %), gastropods (3.6 %)
	F1b	Me18, Me41, Me43, Me44, Me45, Me 46, Me59, Me 63	69.8 to 95.6	0.1 to 9.6	53.8 to 100	0 to 44.4	Red algae (33.7 %), indeterminate carbonate grains (30.2 %), bivalves (10.2 %), bryozoans (5.7 %), lithoclasts (5.2 %), gastropods (4.2 %), foraminifers (1 %)
F2	F2a	Me12, Me19, Me21, Me22, Me03, Me05, Me08, Me09, Me10, Me11, Me 15, Me24, Me26, Me27, Me30, Me31	51.3 to 82.7	0 to 15.3	84.7 to 100	0 to 1.6	Indeterminate carbonate grains (64.6 %), lithoclasts (23 %), gastropods (2.3 %), quartz (2.2 %), bivalves (2 %), red algae (1.6 %)
	F2b	Me02, Me04, Me13, Me14, Me23, Me32, Me33, Me35, Me37	58.1 to 92.0	0 to 12.2	87.8 to 100	0 to 2.5	Indeterminate carbonate grains (33.3 %), lithoclasts (23 %), bivalves (11.2 %), red algae (10.7 %), foraminifers (4.7 %), quartz (3.7 %), gastropods (3.6 %)
	F2c	Me38, Me40, Me47, Me48, Me49, Me50, Me52, Me53, Me56, Met57, Me58, Me62, Me51	82.3 to 95.6	0 to 8.2	91.4 to 100	0 to 1.2	Indeterminate carbonate grains (69.4 %), quartz (10.8 %), lithoclasts (5.7 %), gastropods (3 %), foraminifers (2.9 %), red alage (2.5 %), bivalves (2 %)
F3		Me01, Me06, Me07, Me25, Me34, Me36	22.4 to 79.5	0.2 to 21	79 to 99.8	0 to 0.1	Lithoclasts (56.6 %), indeterminate carbonate grains (24.6 %), bivalves (6.2 %), quartz (4.6 %), red algae (4.2 %), foraminifers (1.3 %)

indeterminate grains observed in thin sections (data not shown) are derived from reworked fragments of bivalves and other molluscs. Furthermore, as the rocks along the Menorcan south coast consist mainly of Late Miocene grainstones and Pleistocene carbonate aeolianites (Pomar et al. 2002; Servera and Riquelme 2004; Fornós et al. 2009) composed of biogenic grains, these would be recycled into the modern sedimentary system by cliff erosion.

According to Péres and Picard (1964), and the overviews on shallow-water carbonate-producing biota by Carante et al. (1988) and Betzler et al. (1997), the most important mobile-substrate biocenosis in this context is that of *Posidonia* meadows. *Posidonia oceanica* is a marine phanerogam endemic to the Mediterranean, which forms meadows that extend from the surface to 40 m of water depth in clear water (Pergent et al. 1995). Several studies have shown their influence and dependence on the nature and dynamics of coastal sediments (e.g. Bouderesque and Jeudy de Grissac 1985; Jeudy de Grissac and Bouderesque 1985; Blanc and Jeudy de Grissac 1989; De Falco et al. 2003, 2008; Gómez-Pujol et al. 2011). Thus, *P. oceanica* is capable of adapting its growth rate to the rate of sediment deposition. In this way, it creates a terraced structure of intertwined roots and rhizomes as well as trapped sediment, which dampens wave energy (e.g. De Falco et al. 2008; Hendriks et al. 2008; Infantes et al. 2009) and affects the composition of bottom sediments by buffering fine sediment re-suspension (e.g. Gacia and Duarte 2001) and increasing the amount of biogenic debris (e.g. Mateo et al. 1997).

Although the carbonate production of *P. oceanica* epiphytes is low (69–157 $g m^{-2} year^{-1}$) compared to other benthic ecosystems (Canals and Ballesteros 1997), sediments collected within meadows of different Mediterranean sites show high biogenic carbonate contents rooted in the associated species

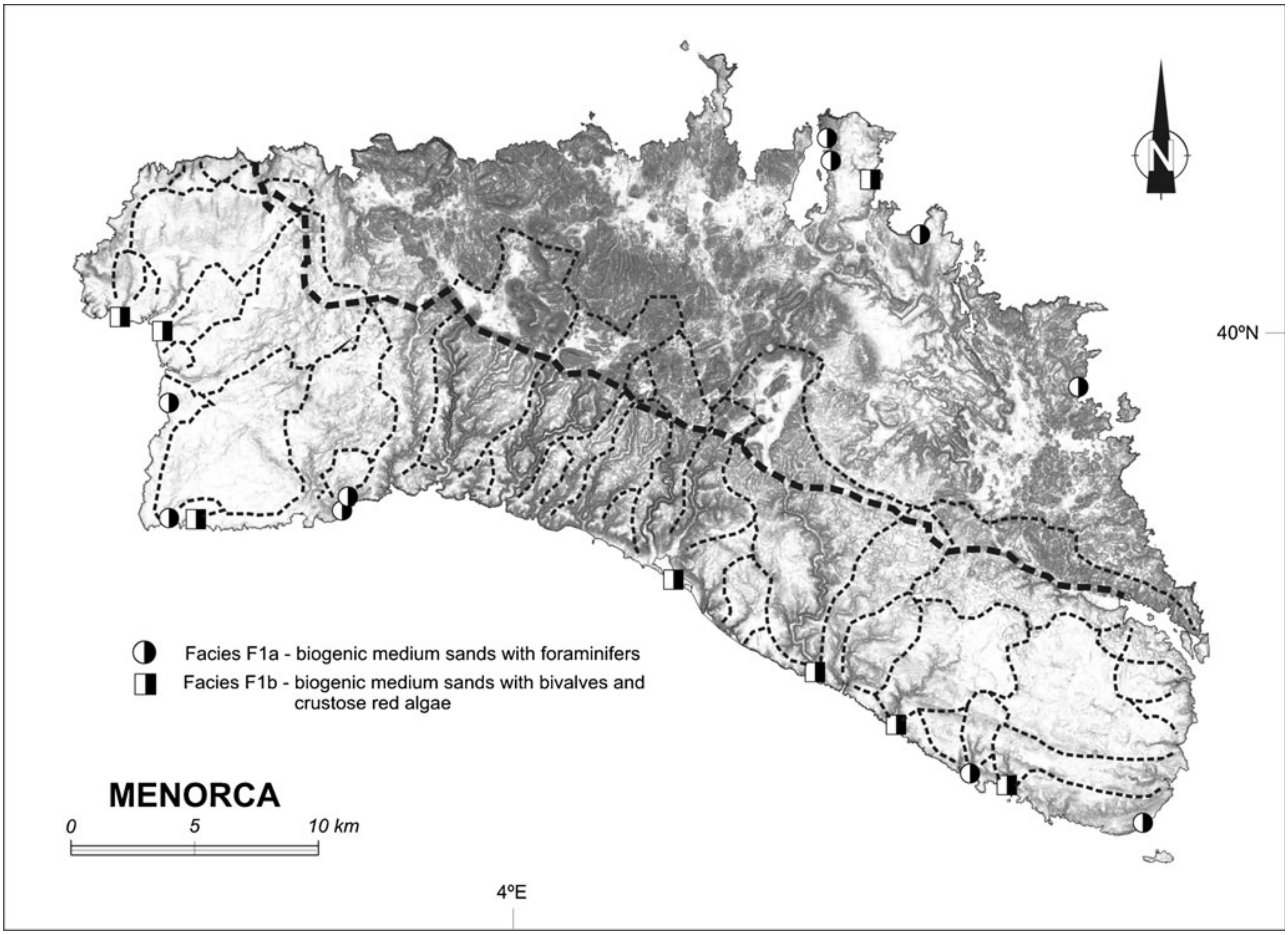

Fig. 3 Spatial distribution of facies F1 (biogenic sands)

assemblages (gastropods, foraminifers, bivalves, echinoids, bryozoans; e.g. Jeudy de Grissac and Bouderesque 1985; Blanc and Jeudy de Grissac 1989; Fornós and Ahr 1997, 2006). Therefore, biogenic carbonate particles produced in the meadows can affect the composition of adjacent beach sediments (De Falco et al. 2000, 2003). Because the uppermost shoreface sediments consist of medium–coarse sand, finer-grained sediments being negligible and streams being ephemeral and without coarse loads (Segura et al. 2007), the sediments of facies F1 (biogenic sands) most probably originate from nearby *Posidonia* seagrass meadows. Furthermore, subfacies F1b—although rich in bivalves, gastropods and foraminifers—is characterised by a high abundance of red algae fragments. Red algae occur in the rhizome compartment of *P. oceanica* meadows and where dim light conditions prevail (Fornós and Ahr 1997). In fact, locations at which subfacies F1b sediments occur correspond to areas of the submarine slope where generally dim light conditions are characteristic. Additionally, Fornós and Ahr (2006) suggest that sediments of the middle ramp around the Balearic Islands consist largely of encrusting, branching and foliose red algae.

Facies F2 (biogenic sands with terrigenous components) occurs both along the Migjorn and the Tramuntana coasts, the distribution of its subfacies reflecting multiple sediment sources. Thus, coarse biogenic sands with terrigenous contributions (subfacies F2a) and medium biogenic sands with terrigenous contributions (subfacies F2b) are restricted to the north coast, the biogenic component contributing at least three times the amount of lithoclasts, and the proportion of skeletal grains defining the main difference between the coarse and medium sands. As the streams along the north coast have a low competence, the supply of lithoclasts is low, and their main source is therefore likely associated with cliff erosion. The comparatively lower carbonate content of the sediment is thus in agreement with the geology of the Tramuntana, which is characterised by carbonate and siliciclastic rocks. Cliff erosion along the north coast is enhanced by the energetic wave climate, which easily reworks the intensively folded, rugged shales and the alternating beds of Triassic mud- and sandstone. Although the biogenic components in the F1 and F2 sediments are similar, the higher proportions of indeterminate grains in the latter are

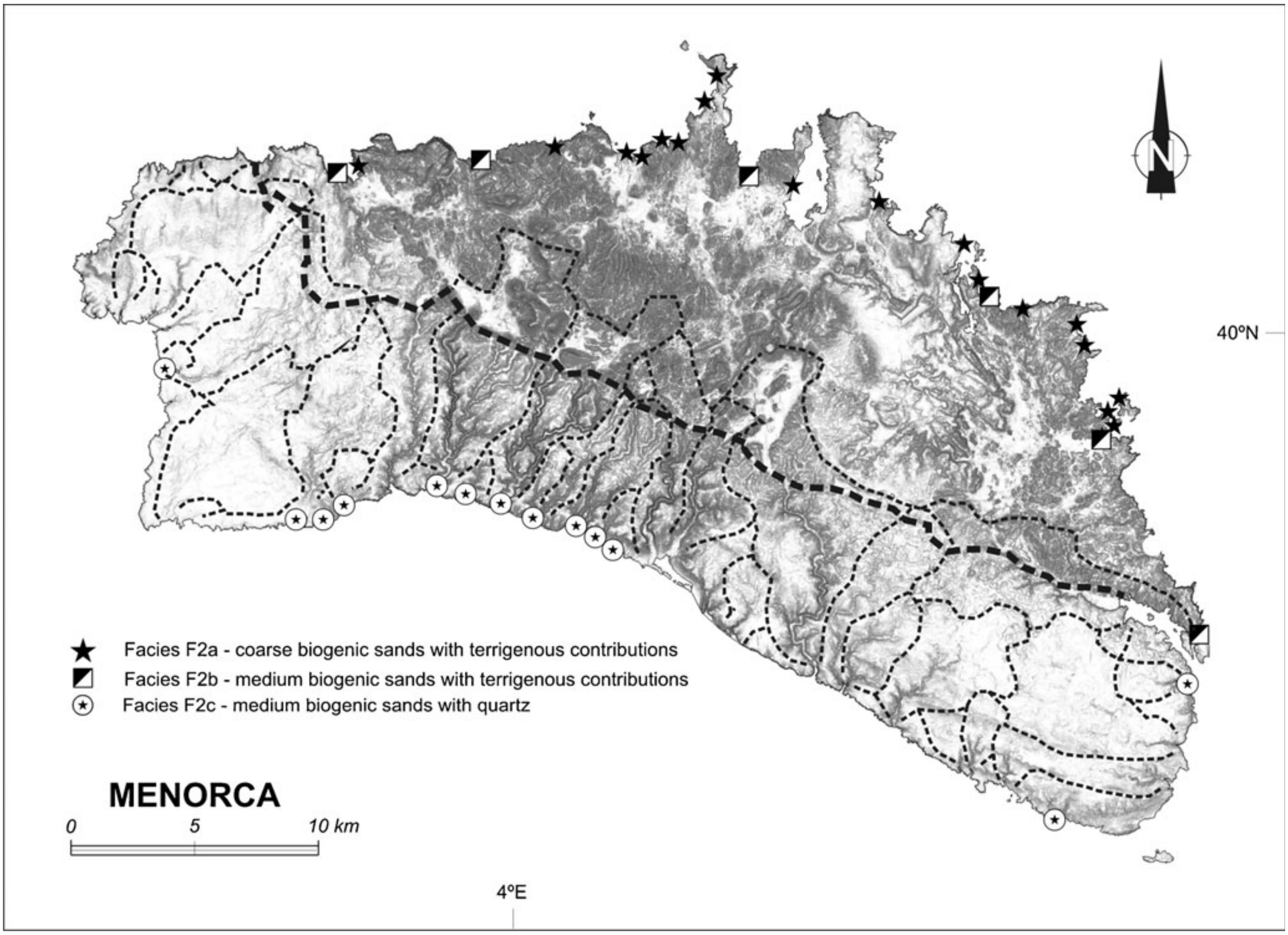

Fig. 4 Spatial distribution of facies F2 (biogenic sands with terrigenous contributions)

in agreement with the more energetic environment, the other carbonate components being supplied from adjacent *P. oceanica* meadows.

The third F2 subfacies—in contrast to the other two—is found only along the south coast of Menorca. Here, the sediment is almost entirely of biogenic origin, with the exception that it is partly enriched in quartz grains. Subfacies F2c is hence defined as consisting of medium biogenic sand with quartz. Despite its patchy distribution, there is a recognisable spatial organisation. Thus, sediments with relatively large amounts of quartz (10 %) occur along the central sector of the Migjorn coast, coinciding with coves and lagoons at the mouths of the fluvio-karstic canyons, whereas those with lower quartz contents are located along the western and eastern margins of the Migjorn coast. As the sources of the biogenic components in these sediments are similar to those discussed above, some explanation for the origin of the quartz grains is required. Geologically, the Migjorn region comprises Late Miocene calcarenites lacking insoluble residues. In spite of this, the mineralogical composition of the soils of the Migjorn (i.e. *terra rossa*) includes allochthonous quartz as the main component, followed by carbonate minerals, clay minerals and feldspar.

On the neighbouring island of Mallorca, it has been shown that similar soils are almost entirely derived from dust-laden rains (Fiol et al. 2005; Fornós et al. 2009; Muhs et al. 2010). In addition, the streams of the central sector of the Migjorn are more deeply incised and entrenched than those in the peripheral areas, their headwaters being located in the more impervious materials of the Tramuntana region where siliciclastic rocks crop out (Gelabert et al. 2005). Thus, despite the low competence of the Migjorn streams (Segura et al. 2007), they evidently do transport some quantities of sand- and mud-sized material rich in quartz during sporadic storms and floods. This scenario adequately explains the spatial distribution and differences among centrally and peripherally located samples of subfacies F2c. It should also be noted that at sample station Me49 there is a very local outcrop of an Early–Middle Miocene sandstone sheet rich in quartz (Fornós 1987), which may supply quartz sand to the study area at present. Because of the upwarping of the Miocene sediment and the generation of an open arch

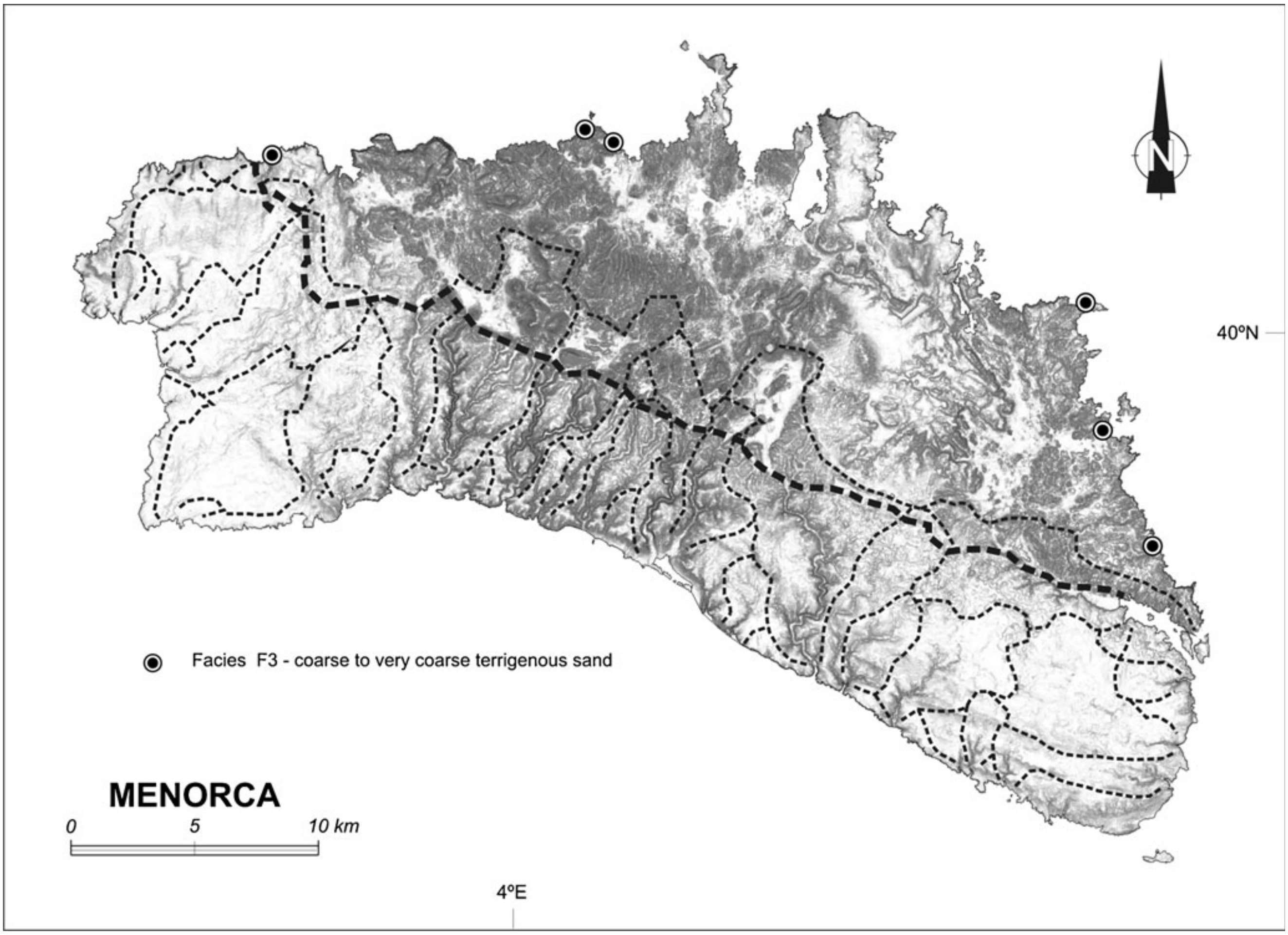

Fig. 5 Spatial distribution of facies F3 (coarse to very coarse terrigenous sand)

with gently dipping limbs, this outcrop is today located at sea level (Gelabert et al. 2005). This very local source of quartz is consistent with the observed distribution of quartz, i.e. higher contents in the central sector of the Migjorn coast and progressively lower contents towards the east and the west.

Finally, the coarse to very coarse terrigenous sands of facies F3 are concentrated along the north coast of the island. They appear to be related to the Mesozoic (Triassic) and Palaeozoic coastal cliffs comprising folded and deformed sandstones and shale exposed to the energetic wave climate generated by northerly gales. Because the streams along the north coast are of low competence and have been shown not to transport significant quantities of sand-size material, the source of the material must be the eroding coastal cliffs. This interpretation is supported by the lithoclast content of the coarser sediment fractions and the bioclast domination in the medium and finer ones. The high proportion of indeterminate biogenic grains is an indicator of high-energy wave reworking, which highlights the important role of carbonate-producing ecosystems in the local coastal sediment production.

The distribution of varying sediment types and grain sizes along the Tramuntana and Migjorn coasts of Menorca not only reflects differences in environmental controls (i.e. waves) and sediment sources, but also reflects the geological and geomorphological evolution of the island landscapes and its contribution to the local character of the uppermost shoreface sediments. Carbonate-rich sediments (marine skeletal facies) reveal the role of the *P. oceanica* meadow ecosystem in the production (mainly associated with the biota) of nearshore and beach sediments. As indicated by the higher proportion of indeterminate grains, the degree of reworking is higher along the north coast than along the south coast, because of the former's more energetic wave climate. The geological differences between the Tramuntana and Migjorn explain the contrasting sediment types, the sediments along the north coast being characterised by mixtures of siliciclastic and carbonate grains whereas, along the Migjorn coast, the sediments are composed predominantly of carbonate grains. This scenario is only interrupted by the Plio-Quaternary geomorphic evolution of the Migjorn drainage system (Gelabert et al. 2005; Segura et al. 2007), which supplies more quartz to the central sector of this coast during sporadic flash floods because the local streams extend headwards into the Tramuntana region. In addition, the Plio-Quaternary deformation has locally exposed Early–Middle Miocene sandstones along the coast, which are being eroded by wave action.

Conclusions

Surf zone sediments from Menorca beaches exhibit a marked distribution pattern that can be attributed to different sediment sources, and to the effectiveness of physical processes as well as geological and geomorphological controls on sediment characteristics:

1. the uppermost shoreface sediments consist primarily of medium to coarse moderately sorted marine biogenic carbonate sands, with some spatial variation controlled mainly by increasing contributions of lithoclasts and quartz along the north coast;
2. sediment input has multiple sources, ranging from onshore to offshore; according to the skeletal assemblages, the carbonate component is produced within the *Posidonia oceanica* meadow ecosystem from where it feeds the shoreface sediments;
3. a patchy distribution of carbonate sediments enriched in quartz grains is observed along the central sector of the south coast, highlighting the contribution by seasonal headwater discharge; this reflects the geomorphological evolution of the island, as well as the role of locally exposed siliciclastic sandstones along the coast as a secondary source of quartz.

In a wider context, this study contributes to the characterisation of the uppermost shoreface–mid-littoral soft bottoms of the Mediterranean continental shelf, and thereby also addresses the nature and evolution of other modern and ancient depositional analogues where the contribution of fluvial sources to nearshore sediments is absent or insignificant.

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