Cliff-front aeolian and colluvial deposits, Mallorca, Western Mediterranean: a record of climatic and environmental change during the last glacial period

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Large, cliff-front accumulations of Late Pleistocene aeolian and colluvial deposits on southeast Mallorca provide a terrestrial record of climatic and environmental change in the Western Mediterranean during the last glacial period. The cliff-front deposits are lithified and form ramps sloping toward the southeast (i.e. seaward). Radiocarbon dating suggests that the deposits formed in Oxygen Isope Stage 3, when sea level was about 50 m lower than today, and the fossil sea-cliff situated 1.5 to 2 km from the palaeo-shore. The aeolian deposits are composed of marine carbonate sand that was transported inland episodically and accumulated in embayments along the fossil sea-cliff. The sand initially formed steadily growing and forward-moving dunes, then sloping sand ramps and finally relatively small ascending dunes. Aeolian accumulation was interrupted by erosion and colluvial ramp formation, and the cliff-front sediments can be divided into two sedimentary cycles each composed of basal colluvial deposits overlain by aeolian deposits. Colluvial deposition probably records relatively humid climatic intervals, whereas aeolian accumulation probably reflects relatively arid climatic intervals. It appears that climatic and environmental changes were rapid, and it is speculated that the dynamics of the cliff-front system on Mallorca were tied to North Atlantic millennial-scale climate oscillations.

Key words: Aeolian sediments, colluvial sediments, climate cycles, Mallorca, Upper Pleistocene.

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The island of Mallorca in the Western Mediterranean is a classic area for the study of Pleistocene carbonate aeolianites and their relationship with climate and sea level change (Butzer & Cuerda 1962; Butzer 1975; Cuerda 1975; Hillaire-Marcel et al. 1996; Hearty 1987; Clemmensen et al. 1997; Rose et al. 1999). Although termed littoral-sedimentary cycles by Butzer (1975) few of the successions on the south coast of Mallorca can actually be classified as true strandline successions in the sense of Ward & Brady (1979). Most Pleistocene successions in this part of the island can either be classified as cliff-top aeolian successions or as cliff-front aeolian successions (cf. Clemmensen et al. 1997; Fornós et al. in press).

The Late Pleistocene cliff-front aeolian deposits, which are considered here, constitute wind-borne marine carbonate sand trapped in front of a prominent cliff that runs along the southeast coast of Mallorca near Llombards (Figs 1, 2). However, at the time of accumulation the cliff was separated from the sea by a kilometre-wide coastal plain. The common occurrence of colluvial deposits between the aeolian deposits makes it possible to classify the system as truly terrestrial. We believe therefore that the system is special in the sense that it holds a record of not only changing environmental conditions at the shoreline (inland aeolian sand transport vs. landscape stabilization), but also of changing geomorphological processes in front of the cliff (aeolian accumulation vs. scree formation). Butzer and Cuerda (1962) related the genesis of the cliff-front accumulations to sea-level oscillations and climatic fluctuations during the last glacial period and speculated that the deposits represented a large part of this glacial period. To test this idea and to get more precise information on the chronology of the cliff-front accumulations we took sediment samples for radiocarbon and optically stimulated luminescence dating.

In this paper we describe the sedimentology and stratigraphy of the cliff-front system and reconstruct

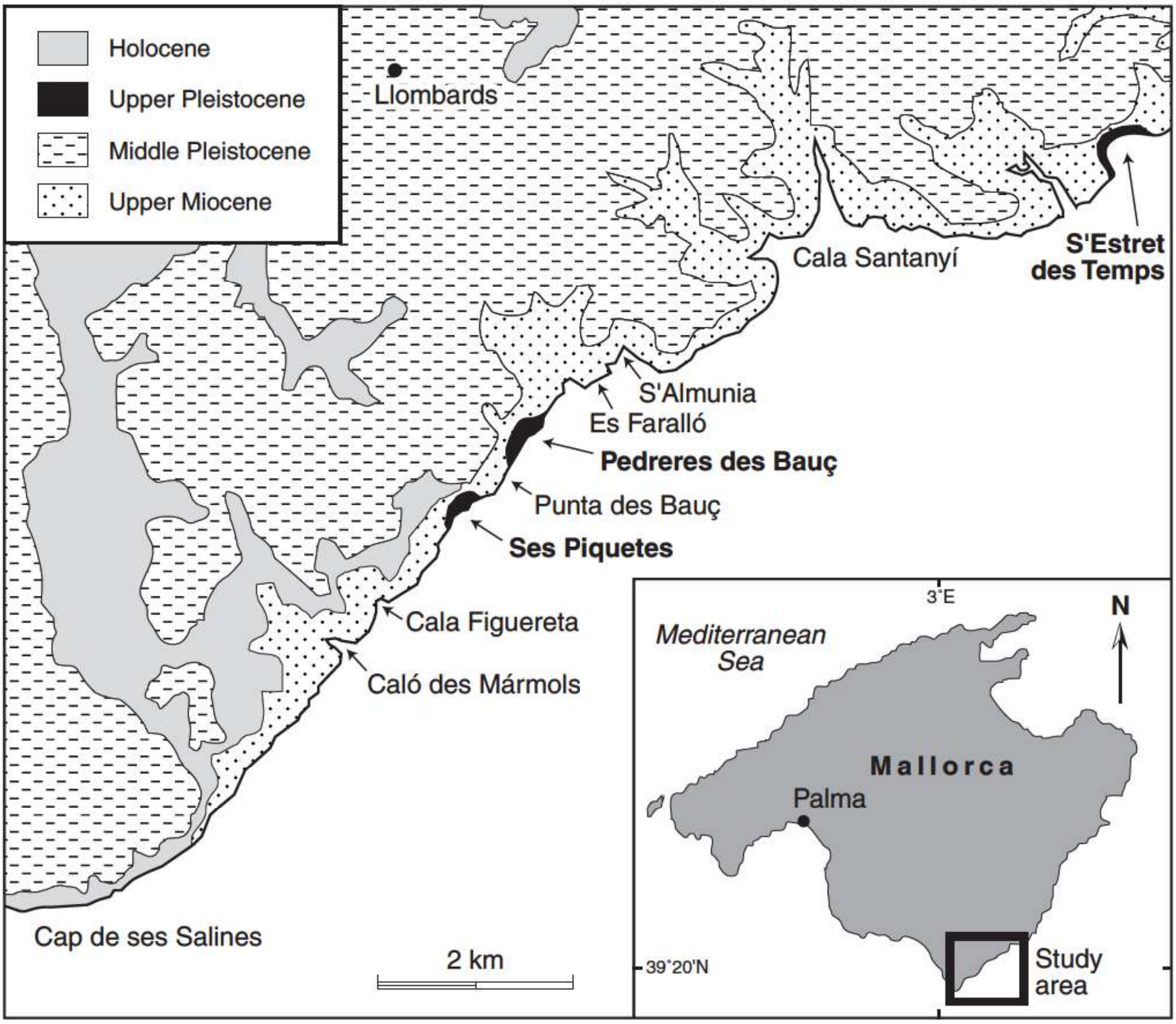


Fig. 1. Geological sketch map of southeast Mallorca showing the location of the studied sites.

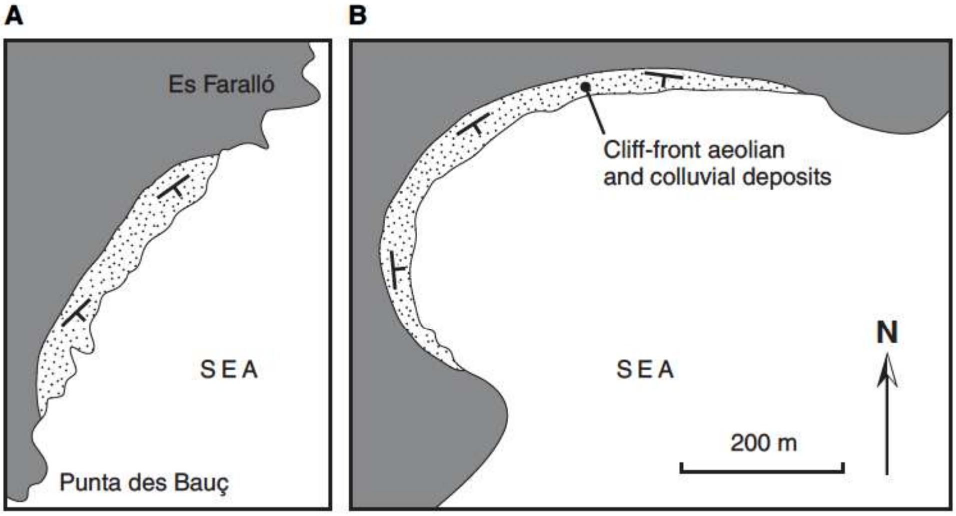
its morphological evolution in response to local environmental change. Based on new datings we discuss the genesis of the cliff-front system in a wider context of millennial-scale climate change during Oxygen Isotope Stage (OIS) 3.

Geological setting

Mallorca comprises two Alpine mountain ranges of folded and thrusted Mesozoic to Middle Miocene strata separated by plains composed of post-orogenic, late Neogene to Pleistocene strata (Pomar et al. 1985). Pleistocene deposits are well exposed at the south coast of Mallorca and characterized by the common occurrence of carbonate aeolianites (Butzer & Cuerda 1962; Butzer 1975; Hearty 1987; Fornós et al. in press). At the studied localities at the coast south of Llombards (Figs 1, 2) the carbonate aeolianites form cliff-front deposits and unconformably overlie Upper Miocene Limestones (Fig. 3; Pomar et al. 1985).

The sedimentology and stratigraphy of such cliff-front accumulations at S'Estret des Temps were documented in some detail by Butzer and Cuerda (1962) and by Clemmensen et al. (1997). The cliff-front deposits lie at the southeastward (seaward) side of a 20–40 m high, relatively steep cliff formed by wave erosion primarily during the last interglacial period and the beginning of the last glacial period (Fig. 3; Butzer & Cuerda 1962). Wave-cut terrasses presumably related to these sea-level highstands are found at +3.3,

Fig. 2. Geomorphological setting of the cliff-front accumulations at Pedreres des Bauç (A) and S'Estret des Temps (B). See Figure 1 for locations.



+4.0, +7.3 and +10.7 m. However, during the last glacial period, when the aeolian and colluvial deposits formed, the cliff was separated from the sea by a coastal plain. Assuming that the deposits formed at about 40 000 BP (see later) when sea level was about 50 m lower than to day (Bradley 1999), it follows from bathymetric maps that the palaeo-shoreline was situated 1.5–2 km seaward of the cliff. Owing to the Holocene sea-level rise, this coastal plain as well as parts of the cliff-front accumulations are now submerged (Fig. 3). Waves constantly erode the seaward parts of the accumulations as well as promontories on the fossil sea-cliff.

The fossil sea-cliff, which is composed of Upper Miocene Limestones (Pomar et al. 1985) possesses embayments and promontories, and the aeolian accumulations are only developed in the bays. However, the geomorphology of the embayments varies much. In the area described in this paper, some are semicircular embayments protected by prominent headlands, whereas others are wide, almost straight embayments protected by short headlands. We describe the stratigraphy and sedimentology of the cliff-front aeolian and colluvial deposits at S'Estret des Temps and at Pedreres des Bauç, and in less detail at Ses Piquetes (Fig. 1). Pedredes des Bauç is a relatively straight embayment that has a width of aproximately 400 m and is bounded by short promontories – Es Faralló and Punta des Bauç (Figs 2, 3). The well-developed cliff-front accumulations reach a height of 35

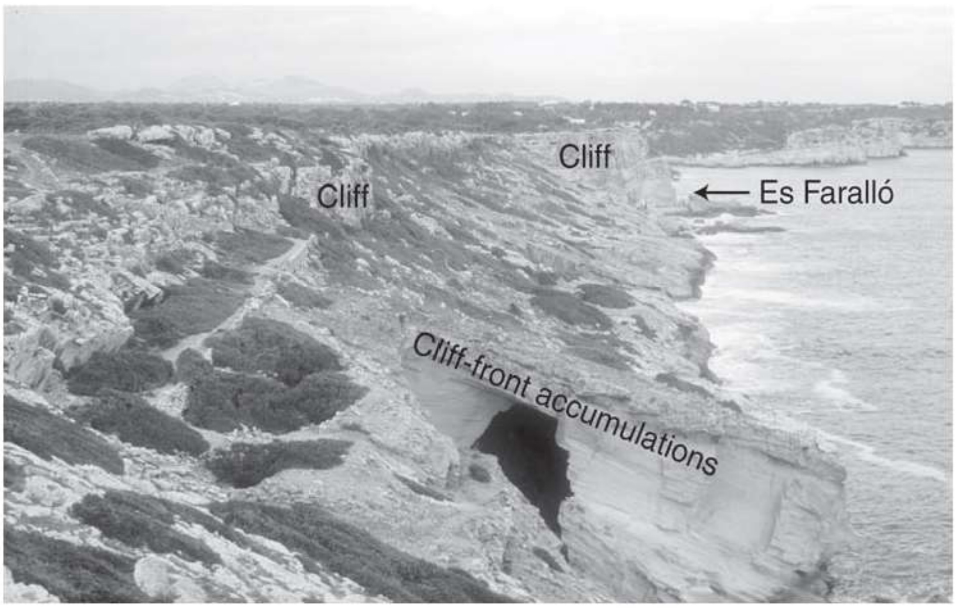


Fig. 3. Field appearance of the Late Pleistocene cliff-front aeolian and colluvial accumulations at Pedreres des Bauç. The cliff, which is composed of Upper Miocene Limestones, was initally formed during the last interglacial period. View from Punta des Bauç towards the northeast. For palaeogeographical setting see Figure 7 and for stratigraphical details see Figure 10.

Table 1. Sedimentary facies, Late Pleistocene cliff-front deposits, Mallorca.

Facies	Characteristics	Genesis
Cliff-front dune deposits	Fine to coarse-grained carbonate sand with a little terrigenous material; wind-ripple lamination and *Myotragus* tracks; large-scale, critical to supercritical dune cross-stratification (accumulations up to 30 m high)	Trapping of wind-transported marine carbonate sand in front of a steep cliff; echo dunes develop into climbing dunes; accumulation controlled by dominant winds from the southeast, and reversed winds between dune and cliff
Sand-ramp deposits	Fine to coarse-grained carbonate sand with some terrigenous material; wind-ripple lamination, *Myotragus* tracks and root casts; seaward-sloping, even, parallel lamination (units up to 3 m thick)	Trapping of carbonate sand on a ramp that developed in front of the cliff; southeastern winds form "climbing" sand-ramp deposits and northwestern winds form "falling" sand-ramp deposits
Colluvial-ramp deposits	Matrix-supported breccias; matrix of silt-rich carbonate sand with some terrigenous material; clasts of limestone (cliff material) or lithified aeolian sediment; clasts have a random or parallel orientation; depositional packages slope away from the cliff and typically thicken downslope (max. thickness is 2 m)	Reworking of aeolian sand, soil products and rock-fall material on ramp during debris-flow events (intense rainfall)
Ascending-dune deposits	Fine to coarse-grained carbonate sand with a litte terrigenous material; wind-ripple and ?sandflow lamination; *Myotragus* tracks, root casts and stem imprints; large-scale landward-dipping cross-stratification (1–2 m thick sets)	Two episodes of carbonate sand accumulation and ascending dune formation on ramp; dunes relatively small and sinous-crested bedforms; dune development controlled by southeastern winds

m above present sea level (Fig. 3). At S'Estret des Temps there is a semicircular bay with a width of approximately 600 m (Fig. 2). Cliff-front aeolian and colluvial deposits are well-developed in the inner part of the bay but are thin or absent towards the promontories. The cliff-front accumulations reach a height of 23 m above present sea level. The studied bays are all open towards the southeast.

Methods

This study of Late Pleistocene cliff-front accumulations comprised mapping of aeolian and colluvial sedimentary units, examination of aeolian architecture and structural style in quarry walls, and bounding surface description and interpretation.

Owing to lithification, the geomorphology of the carbonate aeolianites has been preserved to a large degree, thus facilitating mapping of the aeolian and associated colluvial sediment bodies. Mapping was carried out at a scale of 1: 2500 at Pedreres des Bauç and at S'Estret des Temps. The aeolianites were previously used as local building stones and a number of small quarries are situated in the study area, most quarries being localized at places exposing thick and well-bedded aeolianites. As quarry walls are oriented parallel to or perpendicular to the general strike of the aeolian sediment bodies, it was possible to examine the sedimentary architecture of the aeolian sediment bodies in considerable detail (Clemmensen et al. 1997). In the quarry walls also the contacts between the aeolian and colluvial deposits are well exposed.

In order to understand the chronology of the cliff-front accumulations and to test the idea of Butzer & Cuerda (1962) that the alternating aeolian and colluvial deposition was controlled by sea-level and climate change during the last glacial period, we took sediment samples for radiocarbon dating and for optically stimulated luminescence dating.

The sediments

The Late Pleistocene cliff-front accumulations in the study area comprise the following sedimentary facies:

Fig. 4. Fallen block, Ses Piquetes, showing low-relief wind ripples and two trackways of *Myotragus balearicus*. Block represents the cliff-front dune deposits (Aeolian Unit 1).

cliff-front dune deposits, sand-ramp deposits, colluvial-ramp deposits, and ascending-dune deposits (Table 1).

Cliff-front dune deposits

These sediments constitute the bulk of the cliff-front deposits at the studied localities and overlie basal colluvial deposits. The aeolian dune deposits accumulated in front of a steep, 20–40 m high cliff, and in time the dunes evolved from classic echo dunes to climbing dunes. In agreement with Clemmensen et al. (1997) all these genetically related dune sediments are here termed cliff-front dune deposits to stress the importance of topography in controlling the aeolian accumulations.

The dune deposits are composed of fine- to coarse-grained carbonate sand of marine bioclasts, peloids and more rare ooids. There is a minor admixture of terrigeneous material, mostly very fine grained quartz sand and silt. The sediment is cemented by calcite and the carbonate content of the facies lies between 95 and 99%. The dune deposits are characterized by wind-ripple generated pin-stripe lamination (Clemmensen et al. 1997; Fornós et al. in press). Exposed bedding

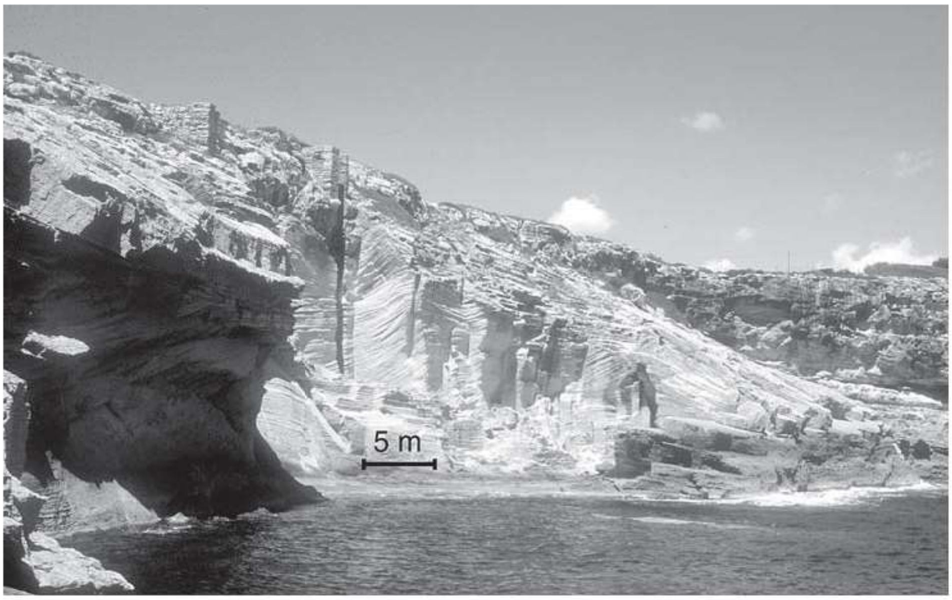


Fig. 5. Cliff-front dune deposits with large-scale cross-bedding, S'Estret des Temps (Aeolian Unit 1). Fossil sea-cliff of Upper Miocene Limestones in the background. View towards the north.

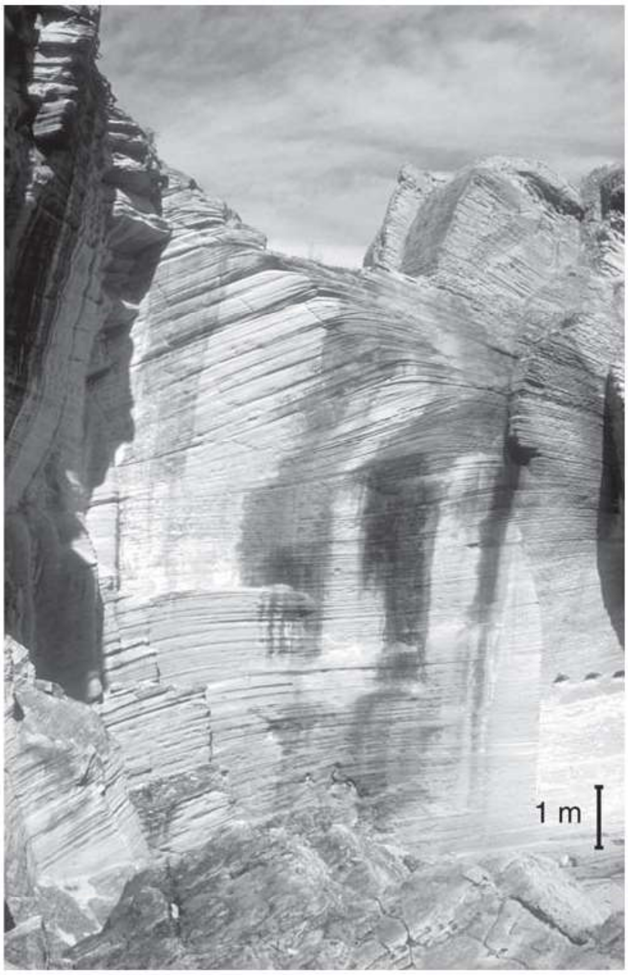


Fig. 6. Close-up of the climbing dune cross-stratification at S'Etret des Temps. Both stoss-side and lee-side strata are preserved. Lee-side strata dip towards the left and the fossil sea-cliff.

planes show low-relief wind ripples and numerous tracks and trackways of the extinct goat-like animal *Myotragus balearicus* (Fig. 4; Fornós et al. in press) as well as invertebrate trace fossils. In vertical sections these tracks are seen as concave up deformation structures that diminish downward, and at some horizons these structures are so abundant that they completely overprint the wind-generated lamination and impart an ichnofabric to the rock. The dune strata are arranged in large-scale, critical to supercritical climbing dune cross-stratification with well-developed seaward facing stoss-side deposits and cliffward facing lee-side deposits (Figs 5, 6; Clemmensen et al. 1997). Angles of climb typically increase towards the cliff and may reach 50°. Stoss surfaces normally dip 15–25° but in the steepest cases reach 31°. Lee-side surfaces typically have dips between 20 and 26° with a few dips reaching 30–32°. The dune profile, as seen in sections, is typically slightly asymmetric, but in places it is nearly symmetrical or even displays a weakly reversed asymmetry. In cross-sections the dune brinkline varies from sharp-crested to rounded. Rounded profiles are typically associated with reactivation surfaces. At S'Estret des Temps dune evolution has been divided into three growth stages (early, intermediate and late) each having a characteristic morphology and sedimentary architecture. Parts of the early stage accumulations of sand, however, are now covered by the sea. At Pedreres des Bauç the exposed part of the dune deposits are primarily composed of intermediate and late stage deposits. At this latter locality the late stage deposits contain a number of complex erosional depressions filled either with well-laminated aeolian sand or with reworked clasts of aeolian sand suggesting penecontemporaneous lithification of the aeolian sediment. At both locations the latest stage dune deposits are in contact with the cliff, although well-developed brinkline deposits seem to be absent in the last few metres before the cliff. The few exposures in this part of the dune bodies may display features such as sand-filled wind scour and cliff-parallel cross-bedding. The uppermost, seaward sloping part of the dune stoss side deposits is erosionally overlain by colluvial deposits.

The strikes of the aeolian dune deposits follow the strike of the embayment (Figs 2, 3). Thus at Pedreres des Bauç, where the embayment is relatively straight and strikes SW–NE, the associated cliff-front dune body also strikes SW–NE. However, at S'Estret des Temps the bay is strongly curved, and the inner part of the bay has strikes between N–S and E–W. The cliff-front aeolian deposits show much more lateral variation in nature here and the strike of individual aeolian sediment bodies changes considerably along the bay (Fig. 2).

The impressive cliff-front dune deposits record the trapping of wind-transported marine carbonate sand in front of a steep cliff. The fine-grained quartz sand and silt were probably brought to the accumulation site from distant sources and primarily deposited as "dust rain". Carbonate sand accumulation was initiated (early stage) some 40 to 60 m in front of the cliff depending on cliff height (Clemmensen et al. 1997). Owing to continued supply of carbonate sand from the southeast, sand piled up and the dune moved slowly forward. At this intermediate stage dune dynamics were seriously influenced by relatively strong reversed winds that were set up between the dune crest and the cliff (cf. Tsoar 1983; Clemmensen et al. 1997). Ideally this reversed airflow should be in balance with the primary air flow and keep the echo dune at a certain distance from the cliff. However, owing to the curved nature of the cliffed embayments and a continued supply of sand the cliff-front dune contin-

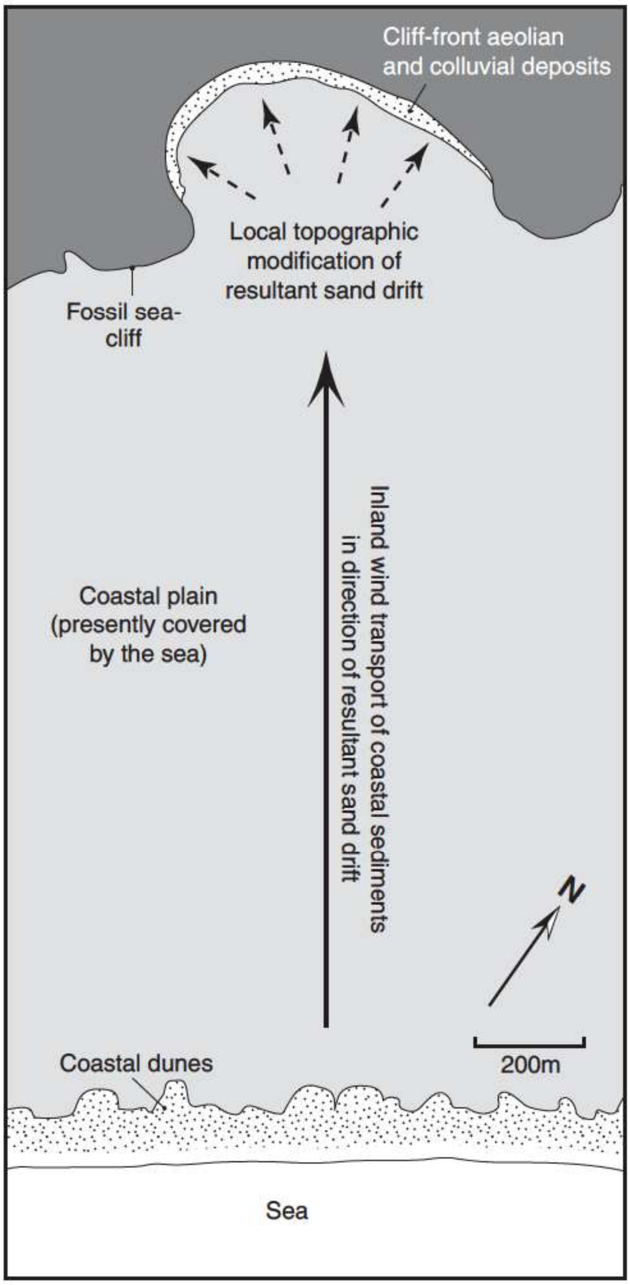


Fig. 7. Palaeogeographic setting of the study area at S'Estret des Temps during formation of the cliff-front dunes. At about 40 000 BP when the cliff-front dunes formed, sea level was about 50 m lower than today, and by use of bathymetric maps the palaeo-shoreline can be placed 1.5 to 2 km southeastward of the present one.

ued to move forward and at most locations eventually came in contact with the cliff (Clemmensen et al. 1997). Exposed dune heights reach about 23 m at S'Estret des Temps and more than 30 m at Pedreres des Bauç, but since the dune bodies continue beneath the present sea level, their true heights are 10–15 m higher.

Sand transport inland was controlled by primary airflow from eastern and southern directions and, to judge from the overall trend of the aeolian accumulations, resultant sand transport was from the southeast (Fig. 7). The local impact of these primary winds (and thereby the local direction of resultant sand drift), however, was strongly controlled by topography of the cliffed embayment. This is particularly well exemplified at the curved embayment at S'Estret des Temps, where the strikes of the cliff-front aeolian accumulations change along the bay (Fig. 2). The reconstructed inland sand transport direction is almost exactly perpendicular to the general trend of the coastline (Fig. 7). Data from modern coastal dunefields on Mallorca also indicate that aeolian sand transport and dunefield dynamics are much dependent on the local shoreline trend (Servera & Rodríguez-Perea 1999). Thus cross-bed data from the study area should not be used to reconstruct regional air flow.

Sand-ramp deposits

These deposits form 1–3 m thick sheet-like packages of aeolian sand that overlie stratified cliff-front dune and colluvial deposits and dip away from the cliff with typical angles around 25°. According to Lancaster & Tchakerian (1996) sand ramps are amalgamated accumulations of aeolian, fluvial and talus deposits that have developed as a result of the interaction of aeolian and piedmont processes adjacent to mountain ranges. The discussed deposits are associated with colluvial deposits, but we here restrict the term sand ramp to cover only the aeolian deposits, while associated colluvial deposits are termed colluvial-ramp deposits. These sand-ramp deposits vary much in nature but, for the sake of simplicity, they can be divided into "climbing" and "falling" sand-ramp deposits.

"Climbing" sand-ramp deposits are best seen at S'Estret des Temps and developed as a sand sheet, 1–2 m thick, that slopes away from the fossil sea-cliff with angles between 20° and 30° (Fig. 8). Nowhere is the contact between the cliff and the "climbing" sand ramp exposed, but it appears that the upper limit of the sand ramp at some places equals the present height of the cliff. The aeolian sediment, as is the case of the cliff-front dune deposit, is a relatively pure carbonate sand composed of marine bioclasts, peloids and very rare ooids with a little admixture of terrigenous matrial. It is cemented by calcite and typically contains around 92% carbonate. The aeolian sediment is well stratified and predominantly show wind-ripple generated pin-stripe lamination. The dip and strike of the sand-ramp deposits are similar to that of

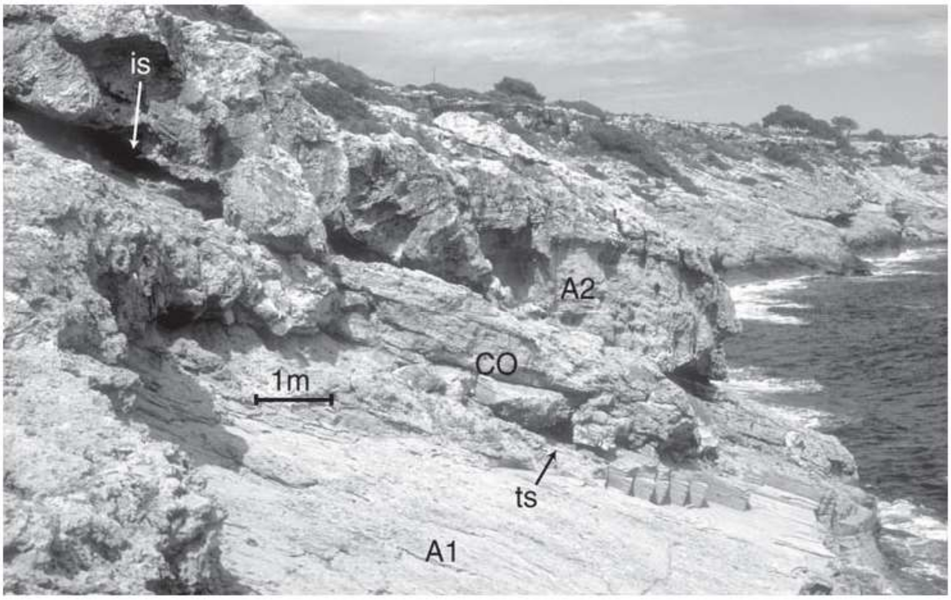


Fig. 8. Sedimentary facies and stratigraphy at S'Estret des Temps. Cliff-front dune deposits (stoss-side strata) of Aeolian Unit 1 (A1) are overlain by colluvial and "climbing" sand-ramp deposits of the Complex Unit (CO), and finally by ascending-dune deposits of Aeolian Unit 2 (A2). Termination surface (ts) and initiation surface (is) are indicated. Fossil sea-cliff towards the left.

the stoss-side strata in the underlying cliff-front dune deposit. There are common root casts near the top of the unit, and abundant tracks and trackways (and related deformation stuctures) of *Myotragus balearicus* throughout the unit.

Prior to sand-ramp deposition any gap between the cliff-front dune and the cliff had been filled with aeolian sediment and the partly lithified dune stoss side covered by colluvial deposits. Thus the "climbing" sand-ramp deposits record the upslope aeolian transport of carbonate sand across the colluvial ramp. Sand accumulated on the ramp partly due to transport rate reduction in front of the cliff edge, partly due to trapping effect of vegetation, but as the sand ramp grew higher it became more and more exposed to wind erosion and much sand may have been transported beyond the cliff edge, especially where the aeolian deposits are most thickly developed. Preservation of these sand-ramp deposits may also have been aided by early lithification.

The "falling" sand-ramp deposits are best seen in the central part of the embayment at Pedreres des Bauç (Fig. 9). These deposits are composed of carbonate sand with some terrigenous material (typically about 15%) and have a reddish yellow colour. The deposits display large-scale low-angle cross-stratification with well-developed bottomsets that downlap onto the underlying colluvial deposits. The cross-beds dip up to 31° towards the southeast. There are scattered root casts throughout the unit and a more densely developed system of root structures near the top of the unit.

The "falling" sand-ramp deposits are thought to represent downslope aeolian transport across the colluvial ramp. This is supported by the nature of the sand containing some terrigenous material, which most likely originated from inland sources. The large content of marine carbonate particles in the aeolian sediment may suggest reworking of previously deposited carbonate sand on the cliff top. Judging from the attitude of the cross-stratification in the "falling" dune deposits, sediment transport was controlled by winds from the west or the northwest.

Colluvial-ramp deposits

These deposits lie at the foot of the fossil sea cliff or drape underlying aeolian deposits and slope away from the cliff. Colluvial is a general term for clastic slope-waste material deposited in the lower part of a topographic escarpment and brought there chiefly by sediment-gravity processes (Blikra & Nemec 1998).

Colluvial deposits form three discrete layers in the study area. The basal colluvial deposit is a red to reddish yellow consolidated silt with scattered angular clasts, and the sediment dips 10–12° seaward. It has a maximum thickness of about 2 m and disconformably overlies wedges of large limestone blocks formed by the collapse of grottoes at the lower part of the fossil sea cliff (Butzer & Cuerda 1962). Unfortunately these deposits are poorly exposed and were not studied in any detail.

The upper two colluvial layers are interbedded with aeolian sediments and typically composed of yellowish red matrix-supported breccias (Figs 8, 9). The clasts are angular limestones (cliff material) or aeoli-

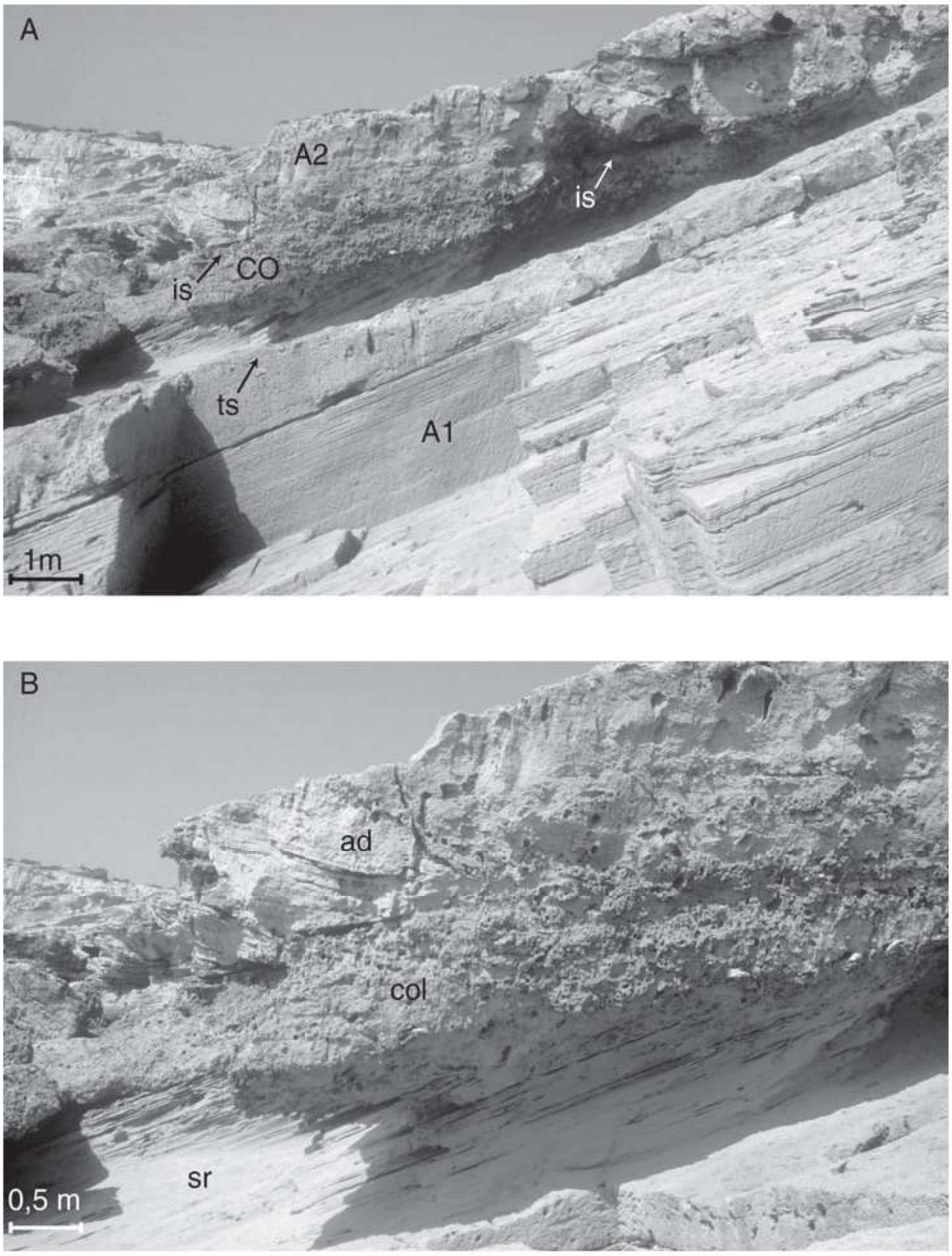


Fig. 9. Sedimentary facies and stratigraphy at Pedreres des Bauç. A. Cliff-front dune deposits (stoss-side strata) of Aeolian Unit 1 (A1) are overlain by colluvial and "falling" sand-ramp deposits of the Complex Unit (CO), and finally overlain by ascending-dune deposits of Aeolian Unit 2 (A2). Termination surface (ts) and initiation surface (is) are indicated. Fossil sea-cliff towards the right.
B. Detail of the Complex Unit. Note the seaward dipping low-angle cross-stratification in the "falling" sand-ramp deposits (sr), the scattered clasts in the colluvial deposit (col), and the landward dipping cross-stratification in the ascending dune (ad).

anites. Clasts vary in size from small pebbles to large boulders, and the clasts occur scattered or in clusters. Clasts are parallel to bedding or randomly orientated. Inverse grading is locally seen, but otherwise the colluvial deposits are massive. The matrix of the breccias is a silt-rich carbonate sand with some terrigenous material. The deposits are cemented by calcite and the carbonate content lies at about 88–96%. The colluvial deposits slope away from the cliff with typical angles at around 25° and thickening downslope, where they reach thicknesses of up to 2 m. The colluvial deposits have a sharp and mostly erosionl contact with underlying aeolian deposits, and a gradational to sharp contact with overlying aeolian deposits. Root casts are common especially near the upper contacts of the deposits.

The basal colluvial deposit probably records episodes of rock-fall and debris flow deposition forming an initial, low-gradient colluvial ramp at the foot of the fossil sea-cliff. The upper colluvial deposits seem to represent debris flow avalanches, which eroded the partly lithified surface of the aeolian sediment and transported slabs of aeolianite downslope together with blocks of limestone (cliff material), which had been emplaced on the sloping surface by rockfall processes. Aeolian sand that accumulated at

Table 2. Pleistocene sedimentary cycles, Mallorca (after Butzer 1975).

Marine hemicycles	Continental hemicycles	Radiometric age (yr)
	A; two generations of coastal dunes	
Z3		
Z2		
Z1		
	B; three aeolian units	
Y3		80 000 ± 5000
Y2		110 000 ± 5000
Y1		125 000 ± 10000
	C; two aeolian units	
X2		190 000 ± 10000
X1		210 000 ± 10000
	D; two aeolian units	
W4		>250 000
W3		
W2		
W1		
	E; three aeolian units	
V2		
V1		
	F; two aeolian units	
U		

the surface between debris flow events as well as reworked soil material (cf. Butzer & Cuerda 1962) formed the matrix of the debris flows. These episodes of debris flows and colluvial-ramp formation were probably triggered by periods of intense rain (Butzer & Cuerda 1962).

Ascending-dune deposits

These deposits form the uppermost part of the cliff-front accumulations, but are not developed at places where the ramp is almost as high as the cliff. The deposits are composed of carbonate sand with only very little terrigenous material. The sand is cemented by calcite and has a typical carbonate content of about 98%. The carbonate grains comprise marine bioclasts and peloids, while ooids are absent. The sand shows cross-stratification dipping landward. At many places, however, the physical stratification is disrupted by root casts, stem imprints or *Myotragus* tracks. The deposits of this unit form two subunits, each composed of a single cross-bedded set with a thickness between 1 and 2 m (Figs 8, 9). Part of the original dune topography is preserved especially in the upper subunit.

The deposits of this unit record two closely related events of ascending-dune formation on the colluvial ramp. The nature of the aeolian sand suggests a new input of wind-transported marine sediment from the coastal area. The dunes were relatively small, sinuous-crested bedforms and dune formation took place during the influence of vegetation. Resultant sand transport was from the southeast and part of the aeolian sand may have been transported across the cliff edge. It appears that the ascending dunes primarily developed at places where the colluvial ramp was significantly lower than the cliff. At these locations there was a reduction in the landward transport rate, thus causing accumulation.

Stratigraphy

Sedimentary units

Butzer (1975) arranged the Pleistocene aeolianites on Mallorca in six continental hemicycles. The studied cliff-front accumulations were placed in a next-to-last hemicycle B (Table 2), which, according to Butzer (1975), formed during the last glacial period. The deposits overlie a number of wave-cut terrasses formed during the last interglacial and the beginning of the last glacial period. Marine deposits formed during the last of these sea-level highstands ("Tyrrhenian III") have U/Th dates of 88 000 and 75 000 BP (Butzer & Cuerda 1962; Butzer 1975) suggesting a correlation with OIS 5a. Beach deposits from this period have also been reported from the northeast coast of Mallorca (Rose et al. 1999).

The stratigraphy of the cliff-front accumultions at the southeast coast of Mallorca was synthesized as follows by Butzer and Cuerda (1962): W-Red 1 (basal colluvial deposit), W-Dune Ia, W-Red 2 (middle colluvial deposits), W-Dune Ib, W-Red 3 (uppermost colluvial deposit), and W-Dune II. In this study we have decided to use a somewhat different stratigraphic terminology since we consider units W-Red 2, W-Dune Ib, and W-Red 3 to belong to the same climate stratigraphic interval, here termed the Complex Unit.

Thus we recognize from the bottom to the top: Basal Colluvial Unit, Aeolian Unit 1, Complex Unit, and Aeolian Unit 2 (Figs 8, 9, 10). The stratigraphy is generally similar at S'Estret des Temps and at Pedredes des Bauç (Fig. 10), but there are some important differences between the two areas as indicated below. At S'Estret des Temps the cliff-front dune deposits of Aeolian Unit 1 display much lateral variation in build up; this is partly a result of the curved nature of the bay and the related variation in local sand drift. The first colluvial deposit in the Complex Unit is relatively thin and sometimes not developed here, and the aeo-

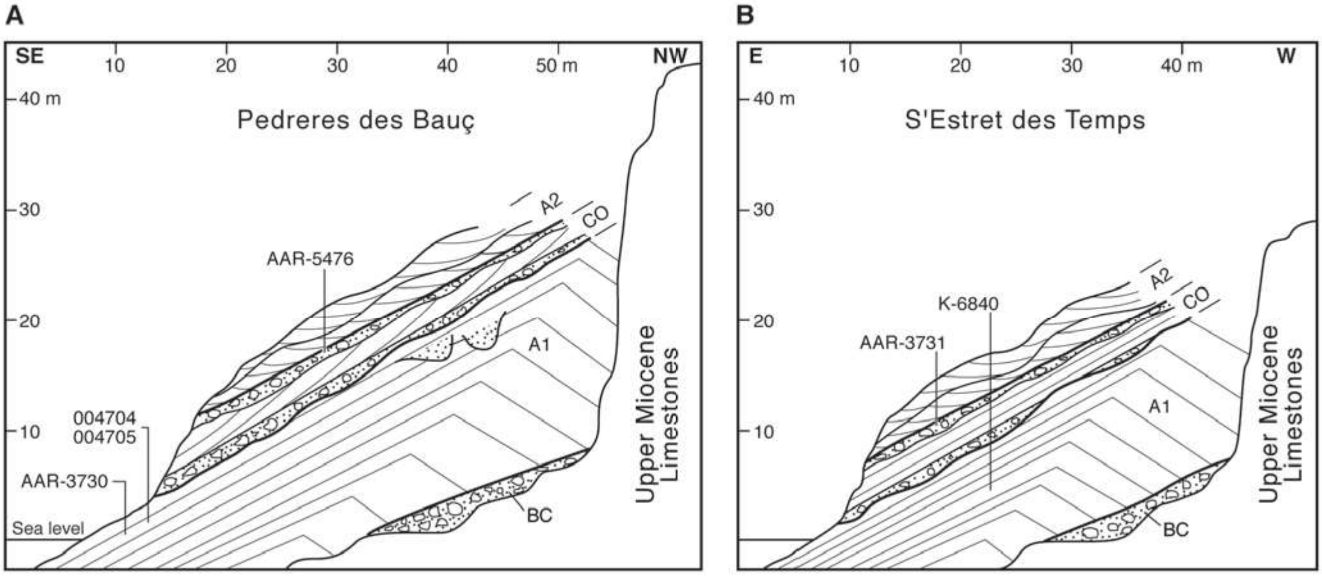


Fig. 10. Idealized stratigraphy of the Late Pleistocene cliff-front accumulations at Pedreres des Bauç (A) and S'Estret de Temps (B). The cliff-front accumulations are composed of colluvial deposits in the Basal Colluvial Unit (BC), cliff-front dune deposits of Aeolian Unit 1 (A1), colluvial and sand-ramp deposist of the Complex Unit (CO), and ascending-dune deposists of Aeolian Unit 2 (A2). Location of sediment samples for ^{14}C dating and OSL dating indicated.

lian deposit of the Complex Unit is primarily developed as a "climbing" sand-ramp deposit. At Pedreres des Bauç the overall nature of the cliff-front dune deposits in Aeolian Unit 1 changes only little along the bay. However in the upper part of these dune deposits there are a number of erosional features partly filled with intraformational clasts. Both colluvial layers in the Complex Unit are well-developed, but show much along-slope and upslope variation in sedimentary characteristics. At Pedreres des Bauç the aeolian layer in the Complex Unit is primarily developed as a "falling" sand-ramp deposit.

The Basal Colluvial Unit contains a rich terrestrial fauna dominated by the snail *Tudorella ferruginea* (Butzer & Cuerda, 1962). The first colluvial deposit in the Complex Unit is barren, while the second colluvial deposit has a rich terrestrial snail fauna with abundant *Tudorella ferruginea*, the endemic gastropods *Trochoidea frater* and *Iberellus companioni*, and rare *Mastus pupa* (Butzer & Cuerda, 1962) that became extinct during the last glacial maximum. In the base of the ascending-dune deposits of Aeolian Unit 2 there are some terrestrial fossils dominated by the gastropod *Eobania vermiculata* (Butzer & Cuerda 1962).

Bounding surfaces

The interbedded aeolian and colluvial deposits in the study area are separated by bounding surfaces of event-stratigraphic significance. Contacts between colluvial and overlying aeolian deposits are mostly sharp and relatively planar; they mark the sudden onset of aeolian activity and are here termed initiation surfaces. In this study we recognize three major initiation surfaces: one at the base of Aeolian Unit 1, one at the base of the aeolian sand deposit in the Complex Unit, and one at the base of Aeolian Unit 2 (Figs 8, 9).

Contacts between aeolian and overlying colluvial deposits show much variation, but they all mark the end of aeolian activity and are accordingly termed termination surfaces. These latter surfaces may also be classified as a special type of super bounding surfaces (cf. Kocurek & Havholm 1993). The termination surfaces are typically erosional and display a relief of up to 1–2 m; there are commonly large slabs of reworked aeolianite above the surface. The termination surfaces show considerable upslope and along-slope variation in sedimentary characteristics. Root casts are common in the uppermost part of the underlying aeolian sediment, which also may contain rainfall-induced fenestrae (cf. Kindler & Strasser 2000). We here recognize two major termination surfaces: one at the top of Aeolian Unit 1 and one at the top of the thin aeolian ramp deposit (Figs 8, 9) in the Complex Unit. A third less well defined termination surface occurs between Aeolian Unit 2 and the young talus deposits.

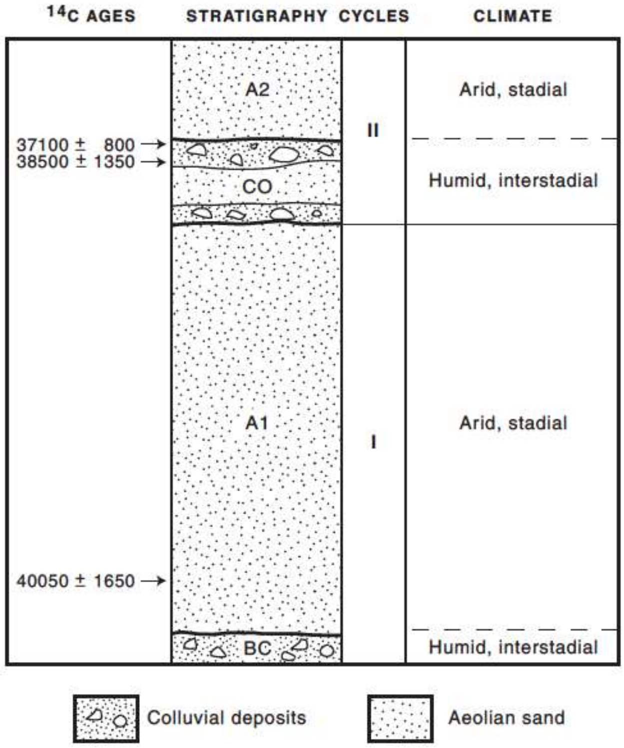


Fig. 11. Age, stratigraphy, sedimentary cycles and climatic interpretation. Late Pleistocene cliff-front accumulations, southeast Mallorca. Basal Colluvial Unit (BC), Aeolian Unit 1 (A1), Complex Unit (CO), Aeolian Unit 2 (A2).

Sedimentary cycles

The sedimentary successions at S'Estret des Temps and Pedreres des Bauç can be divided into two sedimentary cycles. Sedimentary cycle I comprises the sediments in the Basal Colluvial Unit and the cliff-front dune deposits of Aeolian Unit 1 (Fig. 11). However, it must be emphasised that the Basal Colluvial Unit could form an amalgamated deposit and thereby represent more sedimentary cycles without aeolian accumulation. The overlying sedimentary cycle II comprises the Complex Unit and the ascending dune deposits of Aeolian Unit 2 (Fig. 11). The contact between the two sedimentary cycles is a well-developed termination (super bounding) surface at the base of the initial colluvial deposit in the Complex Unit.

Chronology

Radiocarbon dating

Marine shell fragments from the lowermost exposed stoss side deposits of the cliff-front dune deposits at Pedreres des Bauç (Aeolian Unit 1) have an age of 40 050 ± 1650 ^{14}C yr (BP), (Table 3), or ca. 42 500 cal. yr BP (calibrated ages after Kitagawa & van der Plicht 1998), while a bulk sample of carbonate sand from the cliff-front dune deposits at S'Estret des Temps (Aeolian Unit 1) has an age of 28 980 ± 855 ^{14}C yr (BP), (Table 3), or ca. 32 000 cal. yr BP. However, this latter age is considered less reliable owing to diagenetic overprinting. Terrestrial shells from the upper colluvial layer in the Complex Unit at Pedreres des Bauç have an age of 37 100 ± 800 ^{14}C yr (BP), (Table 3), or ca. 40 000 cal. yr BP, and terrestrial shells from a stratigraphically similar colluvial layer at S'Estret des Temps have an age of 38 500 ± 1350 ^{14}C yr (BP), (Table 3), or ca. 41 000 cal. yr BP.

These datings indicate that accumulation of the cliff-front deposits took place during OIS 3, supporting earlier views by Butzer & Cuerda (1962) and Butzer (1975) that the cliff-front deposits formed during the last glacial period. Thus, accumulation of the studied cliff-front deposits took place when sea-level was

Table 3. Radiocarbon dates, Late Pleistocene cliff-front deposits, Mallorca.

Sample no.	Sample type	Collection site	^{14}C age (yr BP)	Reservoir corrected ^{14}C age (yr BP)
AAR-3730	Wind-transported marine shells	Aeolian Unit 1, Pedreres des Bauç	40 450 ± 1650	40 050 ± 1650 (Res. age: 400)
ARR-3731	Terrestrial shells	Colluvial layer, Complex Unit, S'Estret des Temps	38 500 ± 1350	
ARR-5476	Terrestrial shells	Colluvial layer, Complex Unit, Pedreres des Bauç	37 100 ± 800	
K-6840	Wind-transported marine shells (bulk sample)	Aeolian Unit 1, S'Estret des Temps	29 390 ± 855	28 980 ± 855 (Res. age: 410)

Table 4. Optically stimulated luminescence dates, Late Pleistocene cliff-front deposits, Mallorca. The corrected ages use dose rates calculated assuming that the density changed from 1.2 (typical value of recently deposited aeolian carbonate sand on Mallorca) to 1.25 from deposition until 10 000 BP (beginning of the Holocene), and from 1.25 to 2.0 (modern value) between 10 000 BP and the present.

Sample no.	Sample type	Collection site	Age (ka)	Corrected age (ka)
004704	Calcite-cemented dune sediment	Pedreres des Bauç	92 ± 6	59 ± 4
004705	Calcite-cemented dune sediment	Pedreres des Bauç	103 ± 8	65 ± 6

about 50 m lower than today (cf. Bradley 1999) and when the sea-cliff was situated some 1.5–2 km inland (Fig. 7). No marine levels corresponding to OIS 3 have been recorded during the exploration of phreatic crystallization palaeolevels until –30 m in karstic littoral caves (Vesica et al. 2000).

The datings also indicate that formation of Aeolian Unit 1 and overlying Complex Unit was relatively rapid and took only about 2000–3000 years (Fig. 11). Although we have no datings of Aeolian Unit 2 we infer that also this unit formed rapidly. Thus it appears that cliff-front accumulation was restricted to OIS 3 and that it does not record a relatively broad part of the last glacial period as suggested by Butzer & Cuerda (1962).

Luminescence dating

Optically stimulated luminescence (OSL) dating is used here to obtain an independent age determination of the aeolian deposits. Two blocks of carbonate sand, each having a weight of almost 10 kg, were taken from the stoss side deposits of the cliff-front dune (Aeolian Unit 1) at Pedreres des Bauç (Fig. 9). Samples were wrapped in light-proof black plastic bags and transported back to the laboratory. The outer part of the samples was removed in the laboratory and the inner part crushed and treated with HCl to remove the carbonate. From the remaning material quartz grains having grain sizes of about 0.2 mm were selected and measurements of OSL were done using the Single Aliquot Regenerative dose (SAR) protocol (Murray &Wintle 2000). Sample 004704 gave an initial age of 92 000 ± 6000 yr, while sample 004705 gave an initial age of 103 000 ± 10 000 yr (Table 4). These ages are considerably older than the ages given by the ^{14}C dating. Considering the stratigraphic setting of the studied deposits and especially the fact that these cliff-front deposits stratigraphically overlie marine deposits from the Tyrrhenian III (probably OIS 5a) as argued by Butzer &Cuerda (1962) and Butzer (1975), we suggest that the OSL dates are too old. Also, datings of phreatic speleothems in coastal caves on Mallorca by Vesica et al. (2000) show that sea level at this time reached a level of + 2.5 m, and the geomorphology of the cliff-front deposits clearly indicates that aeolian accumulation took place when sea level was lower than now. The OSL age estimates use the modern density values of the samples, and assuming that the bulk of the fresh-water cementation (and density increase) took place in the Holocene (relatively warm and humid period), corrected age estimates of the samples can be given (A.S. Murray, pers. comm. 2001; Table 4). These corrected age estimates of 59 000 and 65 000 years are still older than the radiocarbon dates, but they are considered to support the conclusion that the aeolian deposits formed during a sea-level lowstand in the last glacial period.

Discussion

Studies of pollen in a deep sea core near Sicily indicate that millennial-scale variation in palaeoclimate and vegetation cover in southern Europe between 55 000 and 33 000 BP were tied to global climatic change (Rossignol-Strick & Planchais 1989). Pollen data from Lago Grande di Monticchio in southern Italy from OIS 2 and 3 document the influence of millennial-scale Dansgaard-Oeschger cycles on climate change and vegetation history in the Mediterranean region (Watts et al. 2000). These millennial-scale climatic cycles caused fluctuations between humid and more arid conditions in the Mediterranean region and vegetation changed repeatedly from mixed forest and grassland to grassland (Watts et al. 2000).

The succession on Malloca has been divided into four units and two sedimentary cycles. The nature of these cycles suggest that deposition was controlled by climatic shifts between humid and arid. The ^{14}C dating suggests that accumulation of Aeolian Unit 1 and overlying Complex Unit representing the upper part of sedimentary cycle I and the lower part of sedimentary cycle II took about 2000–3000 years. This duration is in agreement with the duration of the Dansgaard-Oeschger cycles in the North Atlantic (e.g

Rasmussen et al. 1996, Bond et al. 1997), which had typical durations of 1000–3000 years and were well developed during OIS 3 (Bond et al. 1997). Thus it is suggested that the terrestrial succession on Mallorca was controlled by climatic change that in some way was linked to millennial-scale climatic variation in the North Atlantic (cf. Watts et al. 2000).

The precision of our ^{14}C datings and the uncertainty of the exact age of the various Dansgaard-Oeschger cycles (e.g. Dansgaard et al. 1993; Rasmussen et al. 1996; Bond et al. 1997) preclude any exact correlation between the terrestrial deposits on Mallorca and these climatic cycles, although a reasonable estimate, would represent a correlation with Dansgaard-Oeschger cycles 12 and 11, which cover a time span of about 5000 years around 40 000 BP (cf. Rasmussen et al. 1996). Each of these Dansgaard-Oeschger cycles is simply stated to be characterized by a lower part with a relatively warm interstadial climate that gradually becomes colder, and an upper part with a cold stadial climate (Rasmussen et al. 1996). However, in some of the best developed cycles climatic change is more complex with a brief return of warmer conditions just before the stadial. Assuming that the climatic response on Mallorca to stadial-interstadial climatic fluctuation mimics on a shorter time scale the better documented climatic variation on a glacial-interglacial scale (e.g. Frenzel et al. 1992), we suggest that the interstadials resulted in a relatively humid climate, while the stadial caused a relatively arid climate on Mallorca (cf. Watts et al. 2000; Goñi et al. 2000). This suggestion is supported by historical evidence from the Little Ice Age, when climate seems to have been more dry on Mallorca than today (Quadrado 1850; Tarrats 1974/75; Campaner 1984).

The studied succession is composed of two sedimentary cycles (Fig. 11), and the succession is tentatively explained as follows. Increasing precipitation at the beginning of a Dansgaard-Oeschger cycle (interstadial) in OIS 3 at about 40 000 BP caused scree deposition at the foot of the inland cliff forming the Basal Colluvial Unit (Figs 10, 11). Later in cycle I (stadial), the climate changed toward more arid conditions causing a breakdown of vegetation, mobilization of sand at the shoreline and inland transport of sand by southeastern winds. Sand was stopped by the inland cliff and developed into large echo dunes that eventually came into contact with the cliff forming Aeolian Unit 1 (Figs 10, 11). At the beginning of cycle II (interstadial), the climate became again more humid, vegetation was reestablished and inland sand transport stopped. The cliff-front dunes were eroded (termination surface) and covered by colluvial material forming the basal deposit in the Complex Unit (Figs 10, 11). Short-lived wind transport also took place in this interstadial period causing the formation of relatively thin sand ramp deposits. Apparently, wind directions were more variable now and both "climbing" sand-ramp deposits controlled by southeastern or eastern winds and "falling" sand-ramp deposits controlled by northwestern winds formed. Judging from the limited thickness of this aeolian unit, this period of aeolian activity was brief, and the aeolian deposits were eroded again (termination surface formation) and covered by a second colluvial deposit during a return to more humid conditions at the end of the interstadial period (Figs 10, 11). Finally, during the end of cycle II (stadial), the climate once again became more arid and ascending dunes developed under the influence of southeastern winds, forming Aeolian Unit 2 (Figs 10, 11).

If this interpretation is correct there is preserved a terrestrial record of only two Dansgaard-Oeschger cycles on southeast Mallorca. While it is relatively easy to understand that we have no aeolian record of younger cycles (accomodation space in front of the cliff was already filled), it is difficult to explain why aeolian accumulation in the study area first started at about 40 000 BP. Data in Rossignol-Strick & Planchais (1989) suggest that the period around 40 000 BP was unusually dry in the Mediterranean region, and it is possible that only during this overall dry climate, environmental change related to Dansgaard-Oeschger cycles was sufficiently large to cause significant inland wind transport of sand on southern Mallorca.

Conclusions

1. Lithified, cliff-front accumulations of aeolian and colluvial deposits are present in embayments along a fossil sea-cliff on southeast Mallorca.
2. Radiocarbon dating indicates that the cliff-front accumulations formed at about 40 000 yr BP, whereas OSL dating gives somewhat higher ages. We consider that the ^{14}C dating is the more reliable, indicating that the deposits formed at a time when sea level was approximately 50 m lower than now and the cliff situated 1.5–2 km inland.
3. The aeolian deposits are composed of marine carbonate sand with only little terrigenous material. The carbonate sand originated at the shoreline and was transported inland by southeastern winds.
4. The cliff-front sediments can be divided into two sedimentary cycles each intitiated by colluvial deposits and overlain by dune deposits. It is suggested that colluvial deposition records relatively humid climatic intervals, whereas aeolian accumulation records relatively arid climatic intervals.

5. Radiocarbon dating of the deposits indicates that accumulation was rapid and probably covered only a few thousands years. It is suggested that the dynamics of the cliff-front system record millennial-scale interstadial-stadial climatic change during the last glacial period.

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Dansk sammendrag

Sen pleistocæne akkumulationer af æoliske og kolluviale aflejringer optræder flere steder langs klippekysten af det sydøstlige Mallorca. Aflejringerne er hærdnede og deres stratigrafi og sedimentære arkitektur kan studeres i en række tætliggende stenbrud. De æoliske aflejringer består af marint karbonatsand, der blev transporteret landværts af sydøstlige vinde under ilt-isotopstadium 3, da havniveauet var omkring 50 m lavere end nu og klinten sandsynligvis lå 1.5–2 km fra havet. Æolisk sand blev aflejret i indbugtninger langs klinten. Den æoliske akkumulation var episodisk og afbrudt af faser med erosion og kolluvial aflejring. De æoliske processer førte først til dannelsen af store klintfront-klitter, dernæst til opbygningen af sandramper og til sidst til dannelsen af mindre klatrende klitter. Den sedimentære succession består af to sedimentære cykler, der begge indledes af kolluviale aflejringer og afsluttes af æoliske aflejringer. De kolluviale aflejringer afspejler sandsynligvis humide klimaforhold, mens den æoliske sedimentation skete under aride klimaforhold og øget hyppighed af sydøstlige vinde. ^{14}C dateringer viser, at de sedimentære cykler blev aflejret på få tusinde år omkring 40 000 BP. Disse millennium-skala sedimentære cykler kan muligvis relateres til stadial-interstadial kimavariation på den nordlige halvkugle.

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