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ORIGINAL ARTICLE

Facies characteristics and diversity in carbonate eolianites

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Abstract Carbonate eolian dunes can form huge sand bodies along the coasts but are seldom described in the pre-Quaternary record. The study of more than 600 thin-sections collected in present-day, Holocene and Pleistocene dunes from Sardinia, Crete, Cyprus, Tunisia, Morocco, Australia and Baja California confirms that these deposits can be easily misinterpreted as shallow marine at core or thin-section scale. The classical eolian criteria (fine-grained and well-sorted sands) are exceptional in carbonate dunes because the diversity of shapes and densities of carbonate particles lowers the critical shear velocity of the sediment thus blurring the sedimentary structures. Wind carbonate deposits are mainly heterogeneous in size and often coarse-grained. The paucity of eolianites in the pre-Quaternary record could be due to misinterpretation of these deposits. The recognition should be based on converging sedimentological and stratigraphic elements at core scale, and diagenetic (vadose diagenesis, pedogenetic imprints) and petrographical (grain verticalization, scarcity of micritic envelopes, broken and/or reworked foraminifera) clues in thin-section. Bioclastic or oolitic grainstones showing evidence of vadose diagenesis or pedogenetic imprints, should always be suspected of having an eolian origin.

Keywords Eolianites · Coastal dunes · Holocene · Pleistocene · Microfacies

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Introduction

Eolianites are wind-driven subaerial accumulations of carbonate-dominated and carbonate-cemented sand (Brooke 2001). Two types can be differentiated: coastal eolianites and inland eolianites. The latter results from large-scale deflation of exposed carbonate margins and the accumulation of the material far from the coastline (Abegg et al. 2001; Abegg and Hanford 2001). This distinction is important as coastal eolianites build huge, elongated, often accreted sand belts (Aberkan 1989), while inland eolianites form scattered sand bodies infilling continental depressions (Goudie and Sperling 1977; Abegg and Hanford 2001).

Coastal eolianites are formed by material from the deflation of beach deposits and subtidal sediments when exposed to wind during marine lowstand episodes (Abegg et al. 2001). Normal wave-induced shore input and reworking of washover deposits are the main sources of material during sea-level highstands. For a long time, the main coastal carbonate dune record was restricted to icehouse periods, with abundant descriptions for the Late Tertiary and Quaternary times (Johnson 1968; McKee and Ward 1983; see Brooke 2001 for detailed Quaternary inventory) and in the Carboniferous (Abegg and Hanford 2001; Dodd et al. 2001; Smith et al. 2001, see Abegg et al. 2001 for Palaeozoic and Mesozoic detailed inventory).

However, greenhouse eolianites have been discovered in recent years (Kilibarda and Loope 1997; Kindler and Davaud 2001), going against the assumption that eolianite deposition is constrained to icehouse periods, with large glacio-eustatic sea-level fluctuations. These variations would thus not be necessary to the formation of eolianites (Le Guern 2005). Several authors suggested that the scarcity of eolianites in the pre-Quaternary record is due to the low preservation potential of these deposits. However, this assertion is not supported by the fact: eolianites, which are characterized by high permeabilities and porosities, are subjected to the percolation of meteoric water, and contain significant aquifers. They undergo early vadose and phreatic cementation and form ridges which are able to resist coastal erosion even during transgressive phases. Early lithification is probably favoured when aragonite and high-magnesium calcite particles are abundant. Furthermore, non-lithified carbonate dunes may also resist marine transgression, for instance, when located on a leeward side of a structural high (Kilibarda and Loope 1997).

Their high preservation potential (Hasler et al. 2007a) and their occurrence during the Quaternary suggests that eolianites are probably in the fossil record more frequently than suspected, but are misinterpreted as shallow-marine deposits. The aim of this paper is to document the high variability of the facies encountered in present-day, Holocene and Quaternary coastal eolianites and to provide clues for recognizing them at core or thin-section scale.

Palaeogeographical and palaeoecological factors

Many factors can influence the deposition of carbonate coastal dunes. Since these deposits are made of carbonate sands, they depend on the presence of the latter. The position of the continents, the climate and the climatic belts directly influence the carbonate factory. Continental palinspastical and palaeoclimatical reconstructions must be taken into account in the study of pre-Pleistocene eolianites.

Furthermore, the margin architecture appears to be a determinant factor for the eventual deposition of eolianites. Steep rimmed platforms such as the Bahamas are supposed to be producing carbonates dunes only during sea-level highstands, with the lowstand sea-level dropping beneath the rim and stopping sediment input, leaving emerged lands to early diagenesis and cementation (Carew and Mylroie 2001). However, Russell and Johnson (2000) describe important sediment transport over steep cliffs and actual eolian dune formation behind these in Punta Chivato (Baja California Sur, Mexico), demonstrating that abrupt supratidal coastal topography is not an obstacle to eolianite formation, going against Carew and Mylroie's assumption. On the other hand, the incipient rimmed, flat-topped and steep-fronted Rottnest Shelf of western Australia will produce eolianites both during highstands because of the huge area of the carbonate producing flat top (James et al. 1999) and lowstands due to its emersion and exposure to deflation processes (Abegg et al. 2001). Low angle ramps will develop eolianites during both highstands and lowstands (Abegg et al. 2001 and references therein). The presence of reefs may limit the development of eolianites by reducing the sediment's mobility and the onshore sediment transportation. The link between the morphology of the carbonate producing zone and eolian deposition appears to be complex, making simple rules inapplicable from one case to another.

Icehouse periods are characterized by high amplitude variations of sea level due to the formation and meltdown of continental ice-sheets. These fluctuations may favour large-scale emersions and eolianite formation by deflation processes. On the other hand, the important carbonate production during greenhouse times probably generated enough sediment to deposit carbonate coastal dunes by normal shore input even when the amplitude of the sea-level variations is low.

Smaller scale climatic conditions also play an important role on eolianite repartition. Climatic belts constrain their latitudinal deposition between the poleward temperature limit of carbonate production and the warm, tropical, reef-building realm. The permanence and intensity of trade winds favour the development of carbonate eolian deposits. Two latitudinal belts, where the combination of carbonate production and wind factors are optimal and allow maximum coastal dune formation (Brooke 2001) are found between 20° and 40° on both hemispheres (Fig. 1).

The shore and slope morphology is of crucial importance as it contributes to the control of the tidal amplitude and the impact of storms. The tidal amplitude may play an important role in the formation of coastal eolianites. The daily fluctuation of the sea level exposes the shoreface sediment to wind deflation, thus potentially feeding the eolian system twice a day. This process is well documented along the macrotidal coast of Morocco where large active dunes develop (north of Rabat). In the same area, highstand Pleistocene eolianites reaching more than 30 m in thickness (Aberkan 1989; Plaziat et al. 2006), testifying to macrotidal conditions, are found to be associated with foreshore deposits. Moreover, a coast subject to storms may have an important sedimentary input right after these events, via the reworking of the overwash deposits; on the other hand, large storms and hurricanes can erode and even destroy dune belts (Wang and Horwitz 2007).

Carbonate eolian dunes display many features similar to subtidal carbonates (Abegg et al. 2001). Quaternary eolianites show easily distinguishable sedimentary structures at outcrop scale such as large-scale landward-dipping foresets, grainflow, and pinstripe lamination, slump-scar structures, animal tracks and often pedogenetic imprints (Fig. 2). However, at core and thin-section scale, these structures are difficult to distinguish from those generated in subtidal environments. The "climbing translatent ripples" or "pinstripe laminations" (Fig. 2c) are the only unequivocal criterion for discriminating eolian deposits (Loope and Abegg 2001). Pinstripe laminations are inversely graded laminations of a few millimetres thick formed by the progression of wind ripples (Hunter 1977).

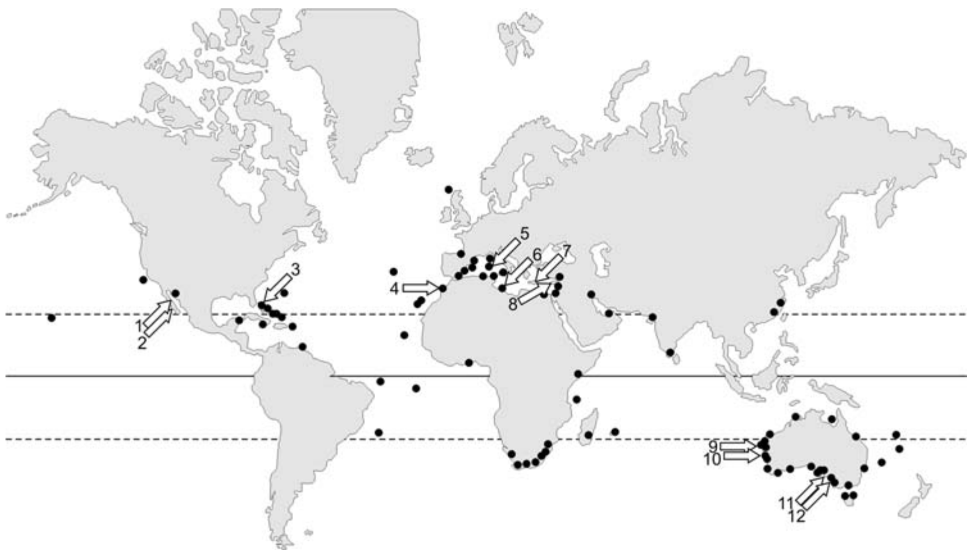


Fig. 1 Geographic repartition of Quaternary eolianites (modified after Brooke 2001). The *white arrows* point to the studied localities presented in this article. *1* Punta Chivato, eastern coast of Baja California, Mexico, *2* Baia Magdalena, western coast of Baja California, Mexico, *3* Joulter Cays, Bahamas, *4* Salé region, North of Rabat, Morocco, *5* Western coast of Sardinia, Italy, *6* Jerba Island and south-eastern coast of Tunisia, Tunisia, *7* Chrissi Island, Crete, *8* Akamas Peninsula, Cyprus Island, Greece, *9* Cloate's Point, Ningaloo Marine Park, Western Australia, *10* Edel Peninsula and Dirk Hartog Island, Shark Bay, Western Australia, *11* Coorong National Park, Southern Australia, *12* Lacepede Bareer, Southern Australia

It is commonly admitted that eolian carbonate dunes are made of well-sorted, well-sieved and laminated sand, with no clasts larger than 3 or 4 mm (Loope and Abegg 2001). Abegg et al. (2001) point out that although calcite has a higher bulk density than quartz, carbonate grains may have a lower apparent density (Yordanova and Hohenegger 2007) because of their intraskeletal (micro-) porosity, thus combining bigger carbonate particles with smaller quartz grains within eolian deposits (Ginsburg 2005; Jorry et al. 2006). This particularity may cause the partial or total concealing of the pinstripe lamination by decrease or absence of the inverse grading, complicating eolianite recognition.

Importance of eolianites

The omnipresence and considerable development of Pleistocene and Holocene eolianites along many coastlines between 50°N and 45°S (Fig. 1) were pointed out by many authors (Glennie 1970; Fairbridge and Johnson 1978; McKee and Ward 1983 among others). Darwin, the first naturalist to describe and understand the processes controlling their formation, was astonished by the extraordinary extension of this facies along the Australian coasts and compared it to the extension of the great coral reefs of the Indian or Pacific oceans (Darwin 1851).

Carbonate coastal dunes may reach huge sizes. For example, Bahamian eolianites represent all emerged land above 7 m of elevation, with a mean altitude between 20 to 30 m, reaching 63 m on Cat Island (Carew and Mylroie 2001). The Western Australian Island of Dirk-Hartog and the Edel Peninsula (Shark Bay) are formed of Pleistocene eolianites, and the active dune field of the Edel Peninsula stretches over 36 km in length and 2 km in width (Le Guern 2005). The Pleisto-Holocene coastal dune complex of the Gharb (north of Rabat, Morocco) is made of four dune belts parallel to the shore, with a width of 2–15 km, and a length of several tens of kilometres, whereas post-Moghrebian deposits and solidified dunes can be found along the Atlantic coast over a distance of 400 km and up to 50 km inland (Aberkan 1989).

From an economic point of view, these huge porous sand bodies contain important aquifers along the present-day coastlines and may represent potential reservoir rocks in the pre-Quaternary record. Their recognition within the stratigraphic record is also important for eustatic reconstructions and sequence stratigraphy interpretations.

Materials and methods

Sampling

More than 600 thin-sections have been collected in present-day, Holocene and Pleistocene dunes along the coasts of Australia, Crete, Cyprus, Tunisia, Morocco and Baja California. The sampling locations are shown on Fig. 1 and briefly summarized in Table 1. The sampling was made both on hard and soft sediment. The aim was to record and analyse in thin-sections all the different facies observed on the field.

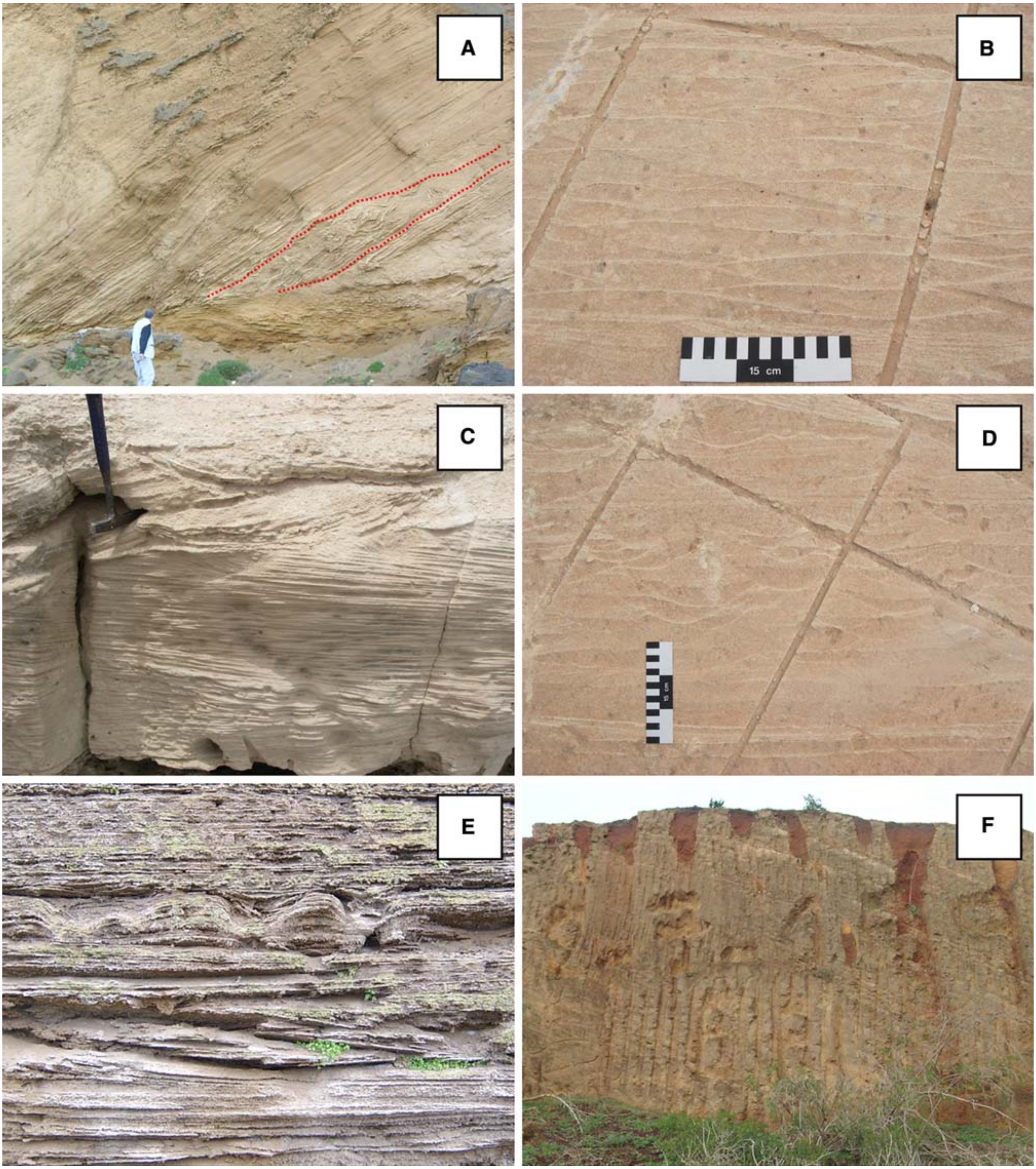


Fig. 2 **a** Large landward dipping foresets with a slumped layer (*dotted lines*). Pleistocene Marine Isotope Stage (MIS) 5e, Salé coast, Morocco. **b** Grainflow lenses. Pleistocene MIS 5e, Slob el Gharbi quarry, Bahiret el Bibane, Tunisia. **c** Pinstripe laminated facies. Holocene 8,660±60 BP, Sidi Salem Fmt, El Kettef harbour. Tunisia. **d** Grainflow slump scars. Pleistocene MIS 5e, Slob el Gharbi quarry, Bahiret el Bibane, Tunisia. **e** Large animal tracks in interdune facies. Picture width: 2.5 m. Holocene, Sidi Boughaba, Morocco. **f** Solution pits in large landward dipping foresets. Height of cliff: 10 m. Pleistocene, Sidi Bou Taibi Quarry, Salé region, Morocco

In lithified dunes, the samples were taken with a strong, battery-operated Bosch Hammer drill, equipped with a water-cooled corer. The cores extracted are 2.5 cm wide and can reach 16 cm in length. The cores were oriented before drilling, and if necessary, different orientations were plugged for the same facies. Once dried, the cores were

Table 1 Geological context of the studied outcrops

Region	Locality	Age	Geological Context	Dimensions (l, w, h)	Petrology	References
Southern Australia	Coorong National Park, Lacepede Bareer	Pleistocene to Recent	Parallel to shore, stacked dune belts, ages increasing towards land	400, 100 km, 100 m	Mixed: 5–70% quartz content	Sprigg (1952, 1958); Short and Hesp (1984); Carr et al. (1999); Le Guern (2005)
Western Australia	Edel Peninsula: Dirk Hartog Island, Dulverton	Pleistocene to Recent	Pleistocene eolianites overlain by actual dunes protecting a hyper saline lagoon	170, 20 km, hectometric thickness	Mixed, with varying quartz content (<50%)	Teichert (1947, 1950); Fairbridge (1950); Logan et al. (1970); Le Guern (2005)
	Cloate's Point, Ningaloo Marine Park	Last Glacial Maximum to Recent	One lithified lowstand eolianite (unit 1), overlain by two transgressive semi-lithified dunes (units 2 and 3), capped by an actual highstand dune (unit 4).	30, 4 km, pluri-decametric thickness	9% quartz for unit 1, 10% quartz for unit 2, 15% quartz for unit 3	Le Guern (2005)
Bahamas	Joulter Cays	950 BP	Highstand dunes on an isolated tropical carbonate platform	1.6, 1.3 km, metric height	100% ooids	Carew and Mylroie (1995, 1997, 2001)
Eastern Mediterranean Sea	Chrissi Island	Holocene 2,400±60 BP and Recent	Actual hummocky dunes and small blowouts (<5 m) (stage 3 of Hesp 1988) over semi-lithified pinstripe laminated dunes	600, 800 m, metric height	Less than 5% quartz	Le Guern (2005); Le Guern and Davaud (2005)
	Cyprus Island	Pleistocene to Holocene	Highstand and lowstand eolianites interfingered with transgressive and regressive sequences on an uplifting coast	5, 1 km, metric to decametric height	Mixed	Kindler et al. (1995)
Tunisia	Sidi Salem (north of Jerba Island), Lella Meriame, El Kettef Harbour	Holocene: 8,660±60 BP	The Sidi Salem formation is made of at least two layers of eolianites: metric dunes overlain by up to 3 m high nebkhas	Discrete outcrops of kilometric length, decametric to hectometric width and up to 10 m thick	Up to 30% of partially oolitized quartz	Jedoui (2000;) Frébourg et al. (2007)
	Slob Ech Chergui	Pleistocene MIS 5e	The Rejiche formation is made of ooid-rich shallow-water to eolian sediments	11, 1 km, up to 15 m thick	Mixed	Jedoui (2000); Hasler et al. (2007a)
Sardinia	Argentiara, Alghero, Is Arùtas, San Giovanni di Sinis, Torre di Corsari and Punto Manga	Pleistocene MIS 5e	Various, see references	Generally, less than 10 m in height. Lateral extention can be hectometric	Mixed	Vardabasso (1953); Comaschi-Caria (1954); Maxia and Pecorini (1968); Pomesano-Cherchi (1968); Caloi et al. (1980); Ulzega and Ozer (1982;) Carboni and Lecca (1985); Ulzega and Hearty (1986); Davaud et al. (1992); Le Guern (2005)
Morocco	Salé coast	Pleistocene to Holocene	Lowstand and highstand dune belts, with age increasing landwards	40 km, 15 km, pluri-decametric thickness	Mixed	Aberkan (1989); Plaziat et al. (2006)
Baja California	Punta Chivato	Pliocene (?) to Recent	Uplifted terraces with associated eolianites, fossil draped dunes, active small dunes and draped dunes	Hectometric lateral extensions for fossil dunes, and decametric patches for active dunes	Mixed	Russel and Johnson (2000)

impregnated with epoxy resin when needed and standard thin-sections were then made in the areas of interest. Hand samples were taken when coring was not possible, with the same orientation protocol.

In unlithified dunes, box-corers were used to extract soft sediment. The box-corers are made out of aluminium electrical cable casings, their section is four on 7 cm, and their length reaches 30 cm. They are equipped with sediment catchers in their front part. Since these boxes have to be hammered into the sediment, extra care was taken to avoid the creation of artefacts. Firstly, the sediment was gently soaked with water around the area of interest to make it cohesive. The box-corer was then pushed lid-off into the wet sediment, oriented along the features to be sampled. The lid was then pushed back in place and the core extracted with care. Once the lid was taken off, the sediment in contact with it was scraped off, and flat plastic boxes of 1×4×6 cm were pushed into the sediment. These small boxes were packed with wet paper inside to prevent desiccation of the sample and retractation artefacts, and were hermetically closed with duct tape.

The samples were placed into a hot air dryer set on 30°C for 48 h then impregnated with epoxy resin under rarefied atmosphere. Thin-sections (3×4.5 cm) were made after the outer borders of the sample were removed in order to have the least disturbed sediment possible. Every thin-section was scanned with a digital scanner with a 4,000 dpi resolution, to build a facies database.

Results and discussion

Broad variety of facies

With the exception of the pinstripe-laminated facies, none of the studied thin-sections show clearly distinguishable evidence of wind-driven deposition. The most striking observation is the average grain size, regardless of the specific sedimentary features. Although fine-grained sand can be observed (Fig. 3), it clearly is not the rule, as indicated by many papers dealing with eolian deposits; grain sizes range from sub-millimetre to pluri-millimetre scales (Figs. 3 and 4). Eolian facies may contain bivalve fragments reaching 1 cm across (Figs. 3h and 4c). In any case, the grains often show little sorting and samples with monomodal granulometry are rare (Fig. 3a, b), the majority of them feature heterogeneous grain sizes (Figs. 3c–i and 4a–c).

Another surprising observation is the scarcity of the diagnostic pinstripe lamination among the collected facies. Although laminated facies are common and represent roughly one half of the collected facies (Figs. 3c, d, i and 4a–c), only a few of them show the characteristic inverse grading of the climbing translatent ripples (Fig. 7f). The other laminated facies display bimodal coarse/finer grained laminae (Figs. 3c, i and 4a). Some others show discrete laminae or coarser, isolated layers among heterogeneous sediment (Fig. 4a, c). The other half of the collected samples is represented by heterogeneous sediment (Fig. 4d, f). These facies are devoid of depositional sedimentary features and are mainly coarse grained.

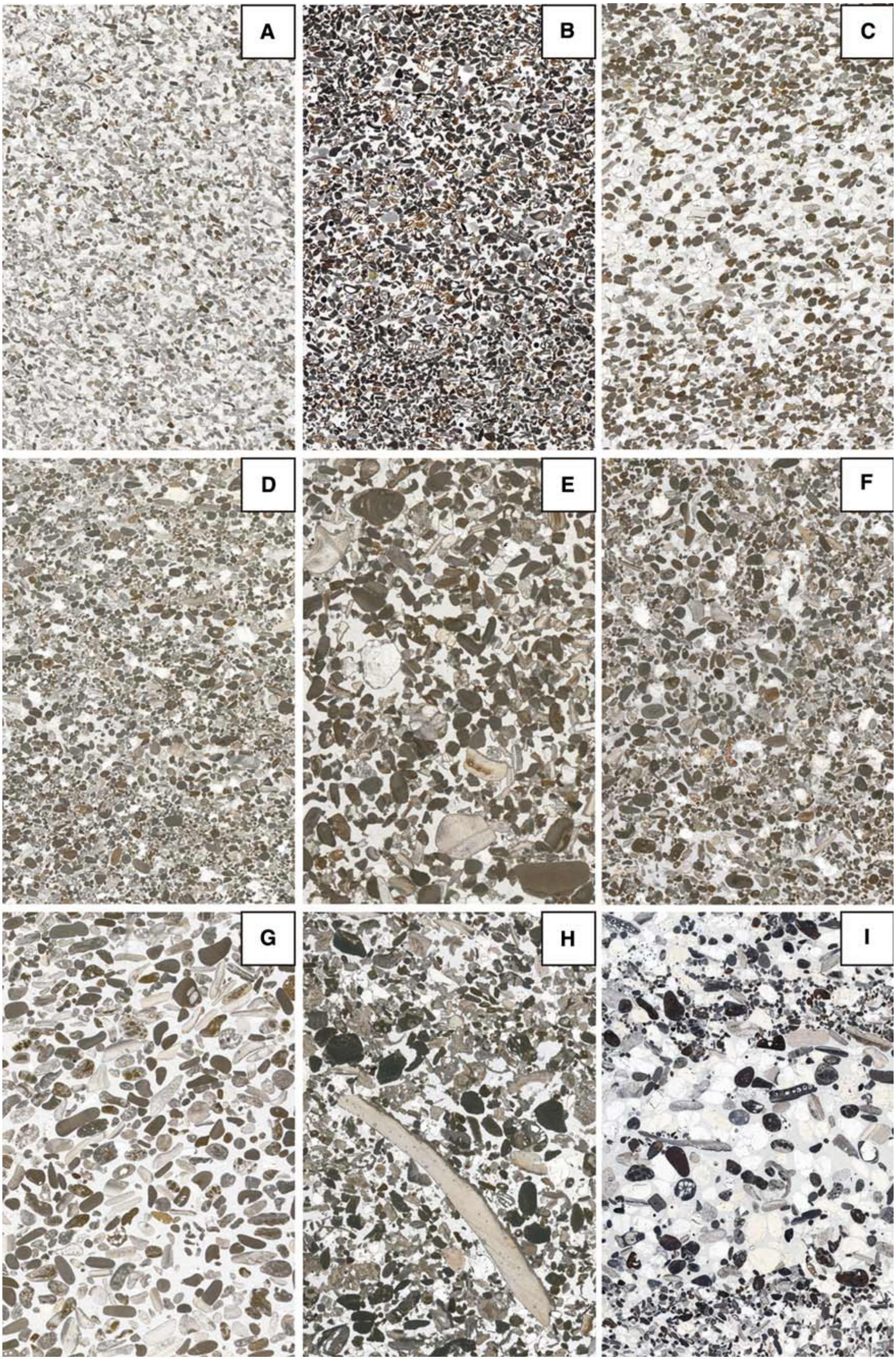
Puzzling petrographic features

Several petrographic features that geologists would not normally associate with the subaerial realm can be encountered.

Lithoclasts can reach important proportions in eolian sediment. These dense particles are more often associated to water-driven erosion and transport than eolian processes. Endoclasts eroded from blowouts in lithified underlying eolianites (Fig. 5b, c) and extraclasts (Fig. 5a) resulting from the erosion of the substrate are often observed, with both kinds reaching coarse sand size (Le Guern and Davaud 2005).

Eolian deposits concentrate bioclasts from the whole carbonate production area. Eolian sands often show assemblages of bioclasts coming from distinct environments and present a higher faunal diversity than the associated subtidal deposits (Le Guern and Davaud 2005). Abundant and well-preserved benthic foraminifera are frequent (Figs. 3b and 4e), as already noted by Evans (1900), Sperling and Goudie (1975), Goudie and Sperling (1977) and Brooke

Fig. 3 **a** Heterogeneous fine-grained facies: bivalve fragments, extraclasts, rounded red algae fragments, foraminifera and foraminifera fragments, quartz. Active dune field, Stony Rise, Western Australia. **b** Heterogeneous fine-grained facies: foraminifera fragments and foraminifera (rotalids, miliolids, textularids), echinoderm plates, bivalve fragments, extraclasts. Active dune field, Chrissi Island, Crete. **c** Laminated bimodal facies: rounded red algae fragments, extraclasts, quartz, reworked foraminifera. Pleistocene, Dirk Hartog Island, Western Australia. **d** Oblique laminated facies showing pinstripe laminations: extraclasts, rounded red algae fragments, reworked foraminifera, bivalve fragments, contemporaneous foraminifera. Active dune field, Ningaloo, Western Australia. **e** Heterogeneous coarse-grained facies: extraclasts, red algae fragments, bivalve fragments, foraminifera, quartz. Pleistocene, Is Arùtas, Sardinia. **f** Heterogeneous coarse-grained facies: rounded red algae fragments, extraclasts, bivalve fragments, broken foraminifera, echinoderm fragments. Pleistocene (MIS 2), Ningaloo, Western Australia. **g** Heterogeneous coarse-grained facies: bivalve fragments, rounded red algae fragments, rounded bryozoans, extraclasts, urchin spines, foraminifera. Note the absence of micritic envelopes around the bioclasts. Active dune field, Millicent, Southern Australia. **h** Heterogeneous coarse-grained and poorly rounded facies: Bivalve fragments, extraclasts, quartz, foraminifera. Pleistocene, Dirk Hartog Island, Western Australia. **i** Laminated coarse-grained facies: bivalve fragments, quartz, extraclasts, rounded bryozoans, rounded echinoderm plates, foraminifera. Active dune field, Edel Peninsula, Western Australia. All thin-sections are vertically oriented and 1 cm wide ▶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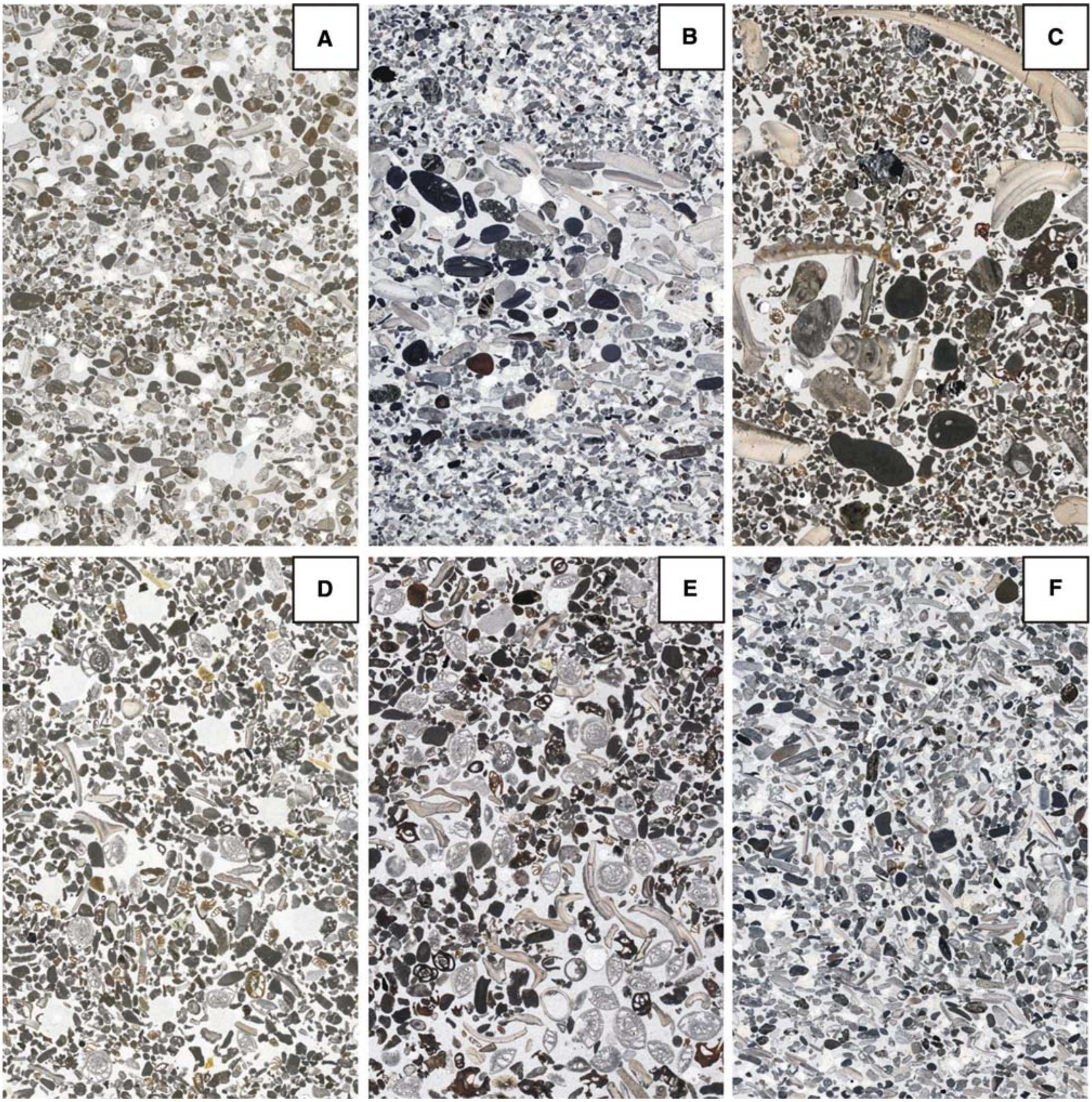

Fig. 4 **a** Laminated coarse-grained facies: extraclasts, reworked foraminifera, contemporaneous foraminifera, bivalve fragments, rounded red algae fragments, quartz. Active dune field, Ningaloo, Western Australia. **b** Laminated coarse-grained facies: Bivalve fragments, extraclasts, rounded bryozoans, echinoderm fragments, quartz. Note the absence of micritic envelopes around the bioclasts. Active dune field, Bishop's Pate, Western Australia. **c** Coarse-grained layer among finer grained sediment: bivalve fragments, extraclasts, gastropod shell, foraminifera, foraminifera fragments. Active dune field, Chrissi Island, Crete. **d** Keystone-vug-crippled eolian facies: rotalid foraminifera, foraminifera fragments, red algae fragments, extraclasts. Active dune field, Chrissi Island, Crete. **e** Foraminifer-dominated eolian facies: rotalid foraminifera, foraminifera fragments, red algae fragments, extraclasts. Active dune field, Chrissi Island, Crete. **f** Displaced and verticalized particles: bivalve fragments, extraclasts, foraminifera, foraminifera fragments, quartz. Active dune field, West Beach, Southern Australia. Note the absence of micritic envelopes around the bioclasts. All thin-sections are vertically oriented and 1 cm wide

(2001). These bioclastic accumulations can be very easily misinterpreted as subtidal sand bars (Fig. 4e).

Planktic foraminifera often found in outer-shelf realms may occur quite frequently in eolianites (Fig. 5d). Contemporaneous and penecontemporaneous tests can be transported tens of kilometres onshore by wind-driven currents. Reworked tests are also common in eolianites overlying planktic foraminifera-bearing marls and clays. These reworked

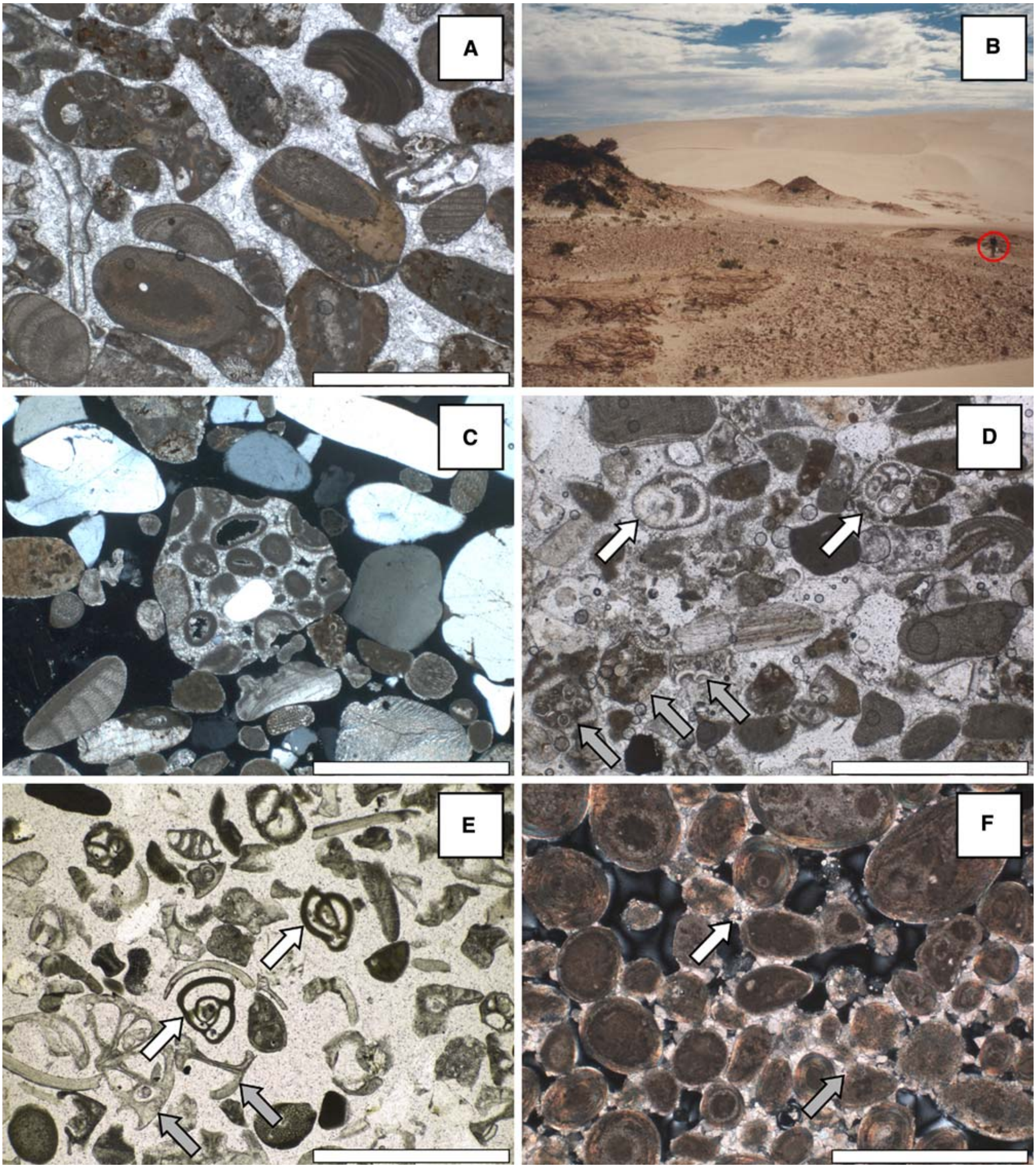

Fig. 5 **a** Lithoclast-dominated facies. Pleistocene, Edel Peninsula, Western Australia. **b** Blow-out in an active dune field (*background*) uncovering lithified Pleistocene dunes (*foreground*). *Person on right side is circled* for scale. **c** Endoclast from a blowout in a Pleistocene underlying eolianite (under polarized light). Actual, Dirk Hartog Island, Western Australia. **d** Reworked planktic foraminifera with micritic fillings and coatings (*white arrows*) and planktic foraminifera-bearing extraclasts (*grey arrows*) from Miocene substratum. Pleistocene, Akamas Peninsula, Cyprus Island. **e** Intact miliolids (*white arrows*) and shattered rotalids (*grey arrows*). Actual, Robe, Southern Australia. **f** Isopachous cement in tight pore network within fine-grained lamina (*grey arrow*), and meniscus cement in the larger pores of the coarse-grained lamina (*white arrow*). Holocene (950 BP), Joulter Cays, Bahamas. *White scalebars* are 1 mm long

foraminifera are seen in extraclasts or derived from these, in which case, they are often surprisingly well preserved but are filled with micrite and are surrounded by a micritic rim (Fig. 5d). If not detected, this reworking can lead to a possible misinterpretation of the age or depositional environment of these facies.

The different types of foraminiferal tests show uneven response to abrasion. The porcellaneous tests seem to be more resistant than hyaline calcitic ones (Fig. 5e). Reworked foraminifera with cemented, spar or micrite infilled chambers are more resistant regardless of the kind of test and do not break into pieces but often show superficial erosion turning them into rounded or sub-rounded clasts.

The presence of fenestrae such as keystone vugs (Fig. 4d) in eolianites is occasionally observed. These features are commonly associated to peritidal environments, but would be linked to rainstorm precipitations in eolian deposits (Bain and Kindler 1994). If typical vadose and meteoric early cementation such as pendant and meniscus cements (Fig. 5f) is encountered most of the time in eolian sediment, isopachous phreatic cements can nevertheless be present in fine-grained laminae. This is due to local saturation of the pore network by percolating meteoric waters. Gypsum cements have been observed in arid and semi-arid climate fossil dune belts. The chances for such cementation to resist a marine transgression or a groundwater table elevation are scarce.

Eolian or high-energy subtidal deposit?

The majority of the facies encountered in this study do not only show a lack of proper eolian recognition criteria, but are also similar to high-energy subtidal deposits. At the core scale, low-angle laminated interdune deposits (Fig. 6a) can be mistaken for beach lamination, especially if keystone-vugs are present (Fig. 4d). Coarse material bearing

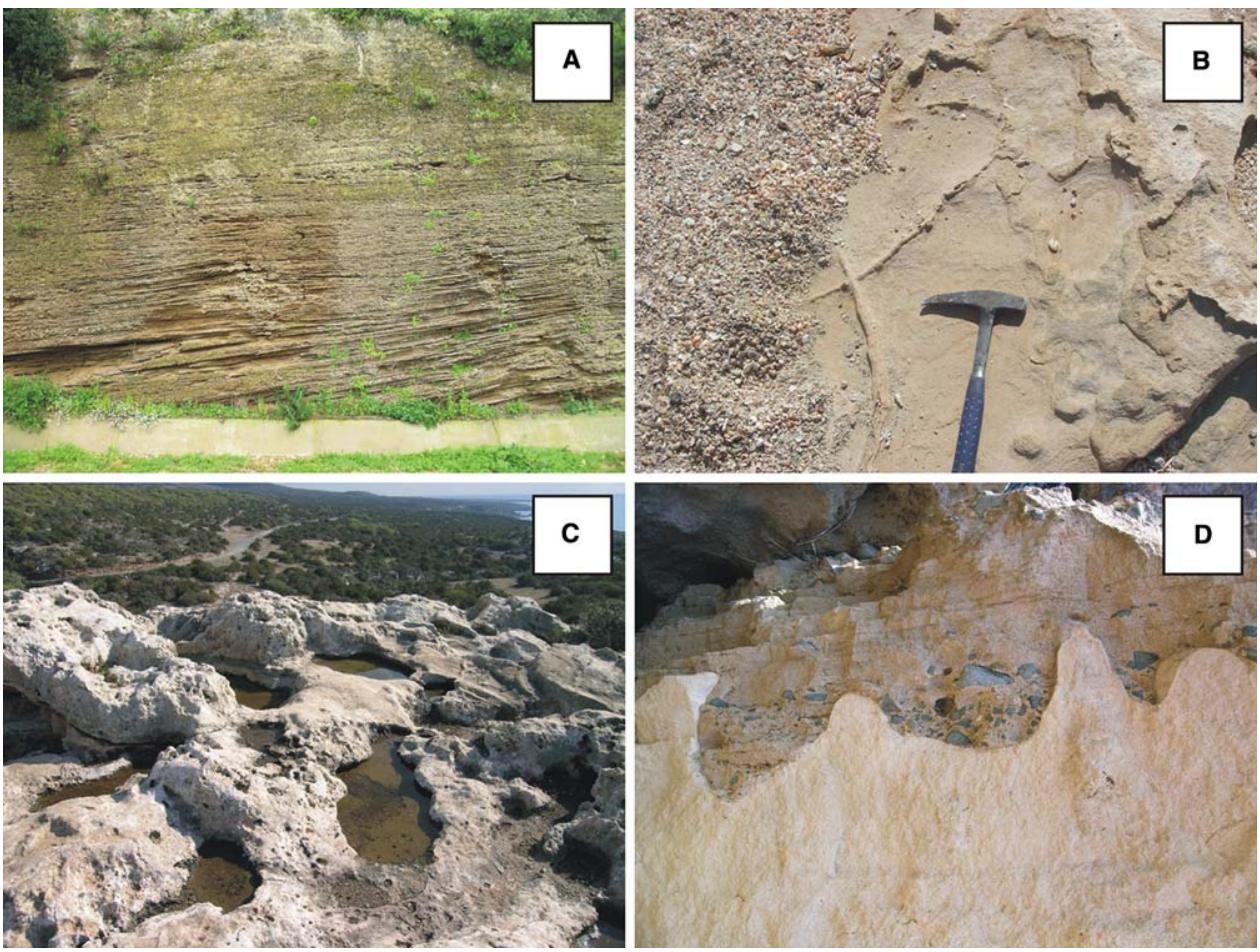

Fig. 6 **a** Interdune planar-bedding. The cliff is 4 m high. Holocene, Sidi Boughaba, Salé region, Morocco. **b** Rhizolites blocked at the surface of an early calcrete crust draping an eolian foreset. Holocene 8,660±60 BP, Sidi Salem Fmt, Lella Meriame, Zarzis region, Tunisia. **c** Karstified impermeable eolianite top. Field of picture: 4 m. Pleistocene, Erimites Hill, Akamas Peninsula, Cyprus Island. **d** Thin calcrete on top of a karstified eolianite overlain and filled by a transgressive marine conglomerate. Field of picture: 1 m. Pleistocene, Protogonos Creek, Akamas Peninsula, Cyprus Island

large-scale landward dipping foresets can be misinterpreted as shoals, as the thickness of these deposits is often similar. The spatial proximity of these facies with the eolian realm complicates the identification of the latter, especially regarding cores, where large-scale features cannot be observed.

At the thin-section scale, all facies, except pinstripe-laminated samples, can be confused with high-energy inner platform subtidal deposits. The stratigraphical proximity of these with the eventual overlying eolian deposits makes the identification by vadose diagenetic imprints dubious. The recognition of an eolian origin in siliciclastic sands relies mainly on the presence of diagnostic (large scale) sedimentary structures. These are and remain visible because of subtle granulometric contrasts. In eolian deposits composed of carbonate particles, the sedimentary structures are less easily detectable because of the lack of grain-size contrast. In fact, bioclastic particles often have intraskeletal porosity that lowers the original calcitic bulk density. As a result, grains with different shapes and different bulk densities may have the same hydrodynamic and aerodynamic behaviour (Jorry et al. 2006) and can be accumulated simultaneously (Fig. 4c), making the sedimentary structures diffuse. This would explain the scarcity of the pinstripe laminations; the process takes place, but the record is blurred.

Some clues for eolianites recognition

Equivocal petrographic features may mislead geologists in their interpretations of eolian deposits, but some peculiar features are often associated with these, and may be of help in recognizing them (see Table 2 for summary).

Due to their subaerial character, eolianites should be systematically subject to early vadose diagenesis and pedogenesis. By definition, dunes are mobile, and the formation of soils requires time and reduced sedimentation rates, making this possible only on a stable substratum. With the exception of contemporaneous vegetation, pedogenesis will only affect inactive dune ridges. If late pedogenesis can affect any kind of rocks or deposits, evidence of early pedogenesis is a good, albeit not absolute, criterion.

Rhizolites are often observed and are very useful at the outcrop scale. However, they do not appear frequently in the thin-sections (Fig. 7a). This is probably due to the fact that the majority of the vegetal imprints were developed on a mobile substratum: the voids left by the decay of the rootlets were filled by the collapse of the unlithified sand, as only big roots leave remnants.

Pedogenetic features such as cryptocrystalline cements, also called chitonic coatings (Fig. 7b), and alveolar textures (Klappa 1980) can also be observed. The chronological relation between these and other diagenetic imprints may give hints of an early pedogenesis. It should be noted that vadose and pedogenetic features may also overprint subtidal sands during regressive episodes. However, one could expect that the major part of these sands will be reworked as beach and backshore deposits during the sea-level decrease unless they were already cemented (Smith et al. 2001). In this case, vadose and pedogenetic features will postdate marine phreatic cements.

Calcretization often occurs early in eolianites. 8,660±60 BP eolianites of the Sidi-Salem formation (Jedoui 2000) show early calcretes thick enough to block now-fossil roots (Fig. 6b). Calcretes develop along stratification planes where layers of finer grains facilitate carbonate precipitation by capillary retention of the water within the smaller pore network. Karstification and solution pipes (Fig. 6c, d) found frequently at the top of Pleistocene dunes are often associated with thin impermeable crusts which are strong enough to resist a marine transgression and preserve the underlying eolianites (Fig. 6d). Such features should be clearly identifiable on cores.

Bioclasts, which are known to develop micritic envelopes in tropical and subtropical shallow realms, are often devoid of these in the studied highstand eolian deposits (Figs. 3g, 4b and 7c). This petrographic feature requires lasting immersion and light-exposure to favour bio-erosive bacterial activity. If bioclasts are rapidly exported in backshore environments, the majority of them will not have time to develop micritic envelopes before being carried and deposited by the wind. Wind-driven transport, itself, also probably abrades partially or totally the micritic envelopes of the grains. Highstand eolian deposits will show rare micritized bioclasts, whereas subtidal deposits will show them in abundance. On the other hand, lowstand eolianites show a higher content of bioclasts with micritic envelopes coming from the deflation of the exposed sediments of the photic zone.

Early vadose diagenetic features such as pendant and meniscus cementation (Fig. 7d) or vadose silts are undoubtedly linked to emergent sediments. However, vadose diagenesis can also affect eustatically or tectonically exposed subtidal sediments. A careful examination of cement stratigraphy could help to distinguish vadose exposed subtidal sand bars from eolian dunes. The preservation of subtidal sand bars during a progressive fall of relative sea level depends not only on their thickness but also and more particularly on the presence of early marine cements. These will prevent sediment dispersion and reworking in the wave action zone. Their exposure in subaerial realms will theoretically promote the development of vadose cement growing over the first generation of phreatic marine cement. If this reasoning is sound, the presence of vadose cements as precursor of lithification must be considered as a strong indication of an eolian origin of the sands.

Table 2 Carbonate eolian deposits versus high-energy subtidal deposits features (modified after Loope and Abegg 2001)

Eolian sands	High-energy subtidal sands
Sedimentary structures	
Large foresets (metric to decametric)	Small foresets (decimetric, rarely to metric)
High angle foresets (>30°)	Low angle foresets (<30°)
Landward dipping foresets	Often bi-directional foresets
Concave-up low angle plane bed (interdune facies)	Seaward dipping or horizontal plane bed (beach facies and shallow sand bars)
Pinstripe laminations, climbing translatent ripples, grainflow scars, grainflow slumps, grainflow lenses	Wavy bedding, current and wave ripples, herring bones, trough cross-bedding, swaley cross-bedding lunar-periodic sigmoids
Only grainstone	Grainstone, rudstone. Packstone and wackestone layers often associated
No mud-drapes	Mud drapes
Adhesion ripples	No adhesion ripples
Keystone-vugs layers along the bedding plane (Bain and Kindler 1994)	Keystone-vugs in beach and washover deposits
Scattered bioturbation (large terrestrial animal footprints, insects, root traces)	Frequent bioturbation due to endofauna (urchins, annelids, bivalves, crustaceans)
Large slumped foresets	Convolute bedding, seismites
High ripple indices (Loope and Abegg 2001)	Low ripple indices (Loope and Abegg 2001)
Petrographic features	
Variable grainsize. Good to poor sorting depending on the nature of the particles. Particle often well rounded	Highly variable grainsize and sorting
Post-deposition grain verticalization (Le Guern and Davaud 2005)	No post-depositional re-arrangement of sediment (bioturbation excepted)
Lithoclasts (endo- and extraclasts)	Lithoclasts (endo- and extraclasts)
Scarcity of micritic envelopes	Abundance of micritic envelopes
Dismantled and shattered foraminifer tests	Abraded foraminifer test (scratches and pits) (Peebles and Lewis 1991; Shroba 1993)
Frequent reworked planktic and benthic foraminifera with micrite filled chamber	“Fresh” foraminifera with clean chambers dominant
Diagenesis	
Vadose cements (meniscus and pendant in large pore network) as first cements	Phreatic cements as first cements
Pedogenetic cryptocrystalline cement as first cementation stage (chitonic rim)	Cryptocrystalline marine cements in beachrock (Neumeier 1998)
Frequent pedogenetic overprints (calcretes, rhizoliths, alveolar structure)	Possible pedogenetic overprints
Preferential calcitic cement growth around clean quartz (Hasler et al. 2007b)	No preferential calcitic growth around clean quartz
Fossils and microfossils	
Planktic foraminifera possibly frequent	Planctic foraminifera rare
Terrestrial gastropods	Bivalves in living position
Terrestrial gastropods coquina	Sea-shell coquina
Mixing of bioclasts and microfauna from different environment	

The study of foraminifera may give hints for the recognition of eolianites. Since eolian deposits are made of allochthonous material, faunal associations from different living realms are mixed together. While autochthonous foraminifera with empty or sparite-filled chambers can be encountered in muddy sediment, foraminifera with micrite-filled chambers cannot occur in grainstones without being reworked. The latter are often observed in eolianites, and although their presence may be equivocal, it still may contribute to recognition. The general conservation state of the test is important. The viscosity of water buffers inter-grain collisions, whereas air-driven transport causes the grains to have violent contacts. Scratching and pitting is commonly observed in underwater conditions, but total dismantlement of tests under water transport would require unrealistic distances in carbonate settings (Peebles and Lewis 1991).

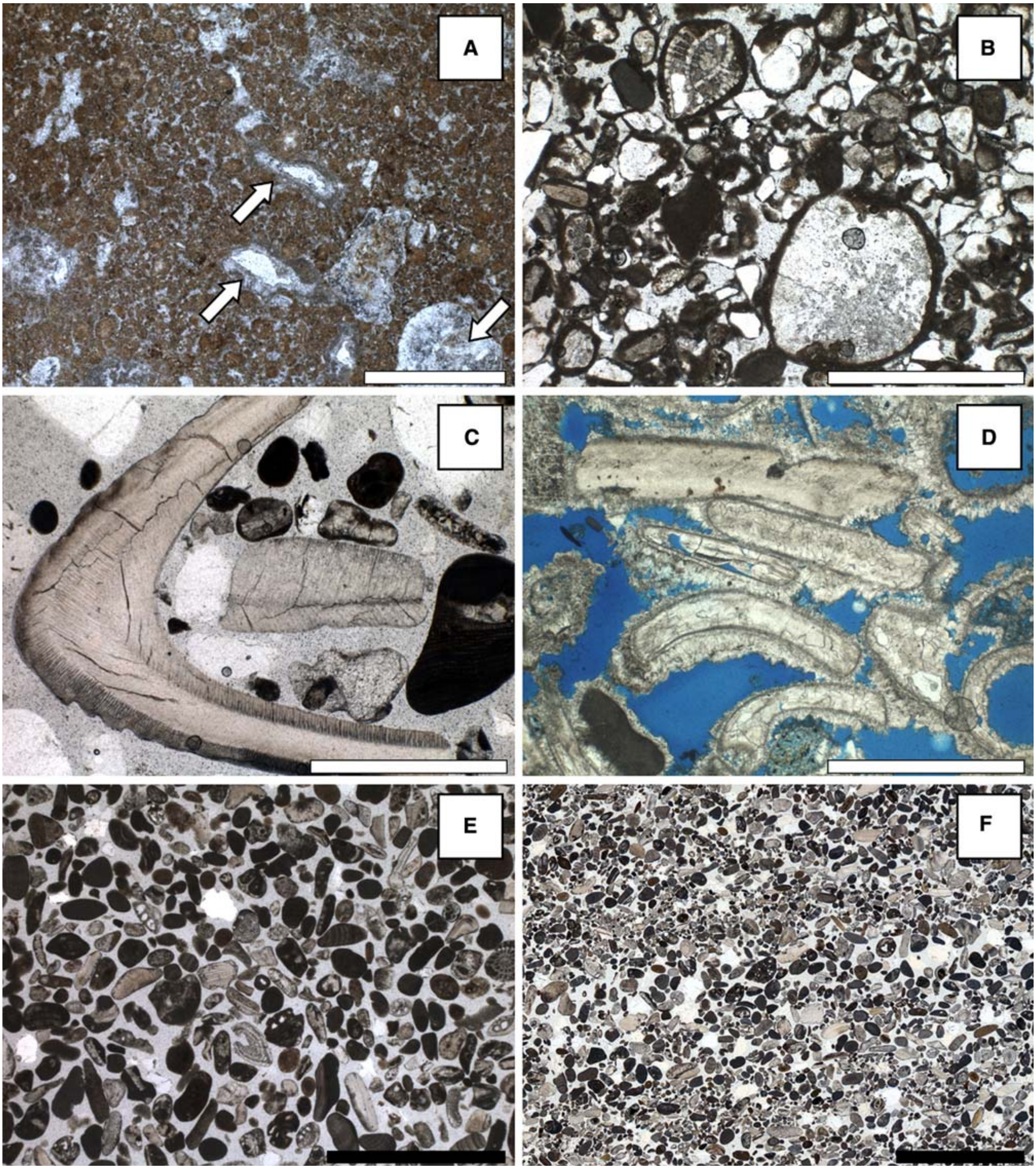

Fig. 7 **a** Pedogenized and rubefied peloidal eolianite with rhizolites (*white arrows*). Pleistocene, East Andros, Bahamas. **b** Pedogenetic cryptocrystalline cement (chitonic rims). San Giovanni, Sardinia, Italy. **c** Bivalve fragments devoid of micritic envelopes. Active dune field, Edel Peninsula, Western Australia. **d** Large pendant cements. Pleistocene, Punta Chivato, Baja California. **e** Verticalized particles. Active dune field, Ningaloo, Western Australia. **f** Pinstripe lamination, Ningaloo, Western Australia. *White scalebars* are 1 mm long, *black scalebars*: 2 mm long. All thin-sections are vertically oriented

In active dune fields, test splitting and chamber breakage of rotalids is observed only after a few kilometres of transport (Figs. 5e and 8a, b). The observations made in this study show that porcellaneous tests of the miliolids are more resistant to wind-driven transport than the hyaline tests of the rotalids, which are prone to break along cleavage planes

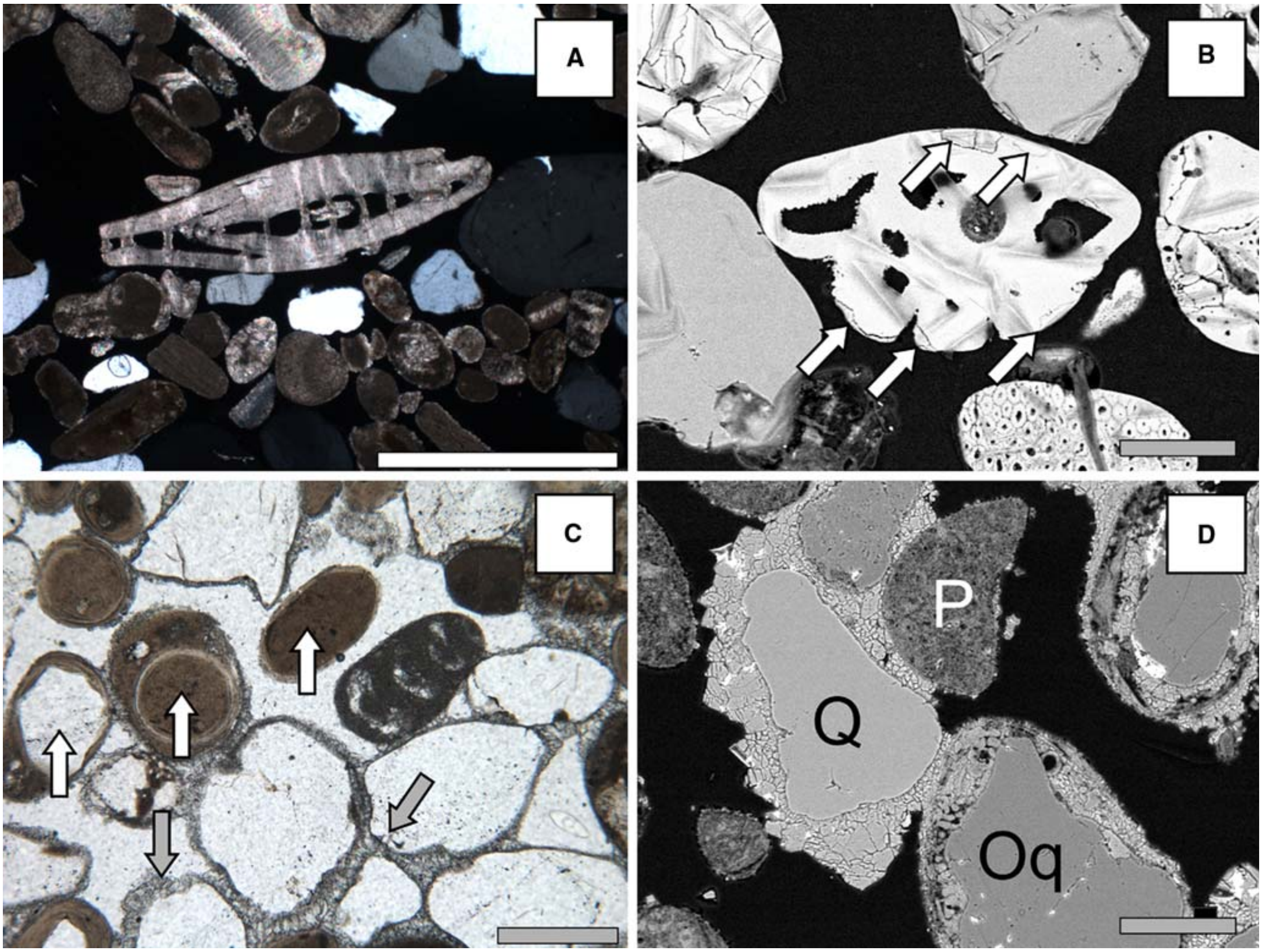

Fig. 8 **a** Broken small nummulite (hyaline foraminifera; under polarized light). Active dune field, Edel Peninsula, Western Australia. **b** SEM back-scattered electron image of an undetermined hyaline foraminifer show impact cracks (*white arrows*). Active dune field, Edel Peninsula, Western Australia. **c** Preferential calcitic cementation around clean quartz (*grey arrow*). Oolitized quartz as well as bioclasts show no cementation (*white arrows*). Holocene 8,660±60 BP, Sidi Salem formation, Lella Meriame, Zarzis region, Tunisia. **d** SEM back-scattered electron image of the calcitic preferential cementation around clean quartz (*Q*). Peloid (*P*) and oolitized quartz (*Oq*) are devoid of cement, excepted in the quartz neighbouring areas. Pleistocene MIS 5e, Slob el Gharbi Quarry, Bahiret el Bibane, Tunisia. *White scalebar* is 1 mm long, *grey scalebars* are 100 µm long

of the radial crystals. The structure of the porcellaneous wall is thick, and made of layers of calcite crystals lattice and protein rich calcite mesh (Peebles and Lewis 1991 and references within), whereas rotalid tests are made of radial calcite crystals and perforated with a more or less complicated and delicate network of channels, pores, or both (Loeblich and Tappan 1964). Large-size calcite crystals break along cleavage planes, and as they are oriented, the fracture propagates itself from the impact point to the neighbouring crystals. SEM studies on polished impregnated sand confirm this phenomenon (Fig. 8b).

Typical eolian features

This study points out that if reliable criteria for eolianite recognition do exist, their presence tends to be rare, due to the specificity of the conditions needed for their formation and preservation. In mixed siliciclastic/carbonate eolianites, preferential cementation around quartz grains has been noticed (Fig. 8c, d). This could be due to the hydrophilous character of quartz, causing the retention of percolating waters (Hasler et al. 2007b). This phenomenon is not documented in phreatic conditions and may be an additional recognition criterion of early vadose diagenesis.

The major part of the particles is oriented parallel to the foreset plane. However post-depositional vertical reorientation of the grains can be observed in eolianites (Fig. 7e). This verticalization would be due to the percolation of meteoric water and surface tensions occurring during evaporation of water menisci (Le Guern and Davaud 2005). This feature is often associated laterally with grain displacement patterns (Fig. 4f) probably due to the water percolation and air escape processes. This feature has so far only been described in eolianites and may be a good recognition criterion when present.

The only reliable and unequivocal recognition criterion for eolian deposits is the presence of pinstripe laminations (Figs. 3d and 7f) generated by the lateral and vertical migration of wind ripples (Hunter 1977). Whilst this sedimentary structure is common in quartz sand, the heterogeneity of carbonate sand often conceals the laminations, with the exception of homogeneous media such as oolitic sands. Despite the frequency of the depositional process, the record of these inverse graded, millimetre scale laminae remains rather rare in carbonates eolian dunes.

Conclusions

Due to intraskeletal porosity, most carbonate bioclasts can reach low densities and require low critical shear velocities to be transported. Wind carbonate deposits are mainly heterogeneous in size and often coarse-grained. The diagnostic criterion of fine, well-sorted and laminated sand facies commonly applied in siliciclastic sedimentology for eolian recognition is exceptional in carbonate deposits and therefore cannot be used.

Due to the different hydro- and aerodynamic behaviour of particles, the nature of carbonate sands and their variable densities implies a broad range of facies. Although the sedimentary processes are the same for monomineral sands such as quartz sand, and carbonate sands, the diversity of the shapes and densities of the bioclasts will buffer the grain size contrasts and blur sedimentary structures.

In the absence of frequently recurring and reliable diagnostic criteria for eolianite recognition at the core or thin-section scales the use of a combination of converging clues becomes necessary (Table 2). The stratigraphical succession of the over- and underlying deposits, together with the diagenetic sequences may give precious clues for the discrimination of eolianites. The analysis of the grains' surface can reveal wind-driven transportation. The general state of foraminiferal tests (especially rotalids) records the transport conditions. Test splitting and chamber breakage are common in eolianites. The scarcity of micritic envelopes around bioclasts can also be a good proxy for highstand eolianites from tropical realms.

The consequence of the lack of proper and easily distinguishable criteria for the recognition of eolianites is that these fossil dunes are probably much more present in the fossil record than described or reckoned, but are not yet correctly identified. When studying bioclastic or oolitic grainstones showing evidence of vadose diagenesis or pedogenic imprints, one should always wonder whether these deposits could have an eolian origin, even if they are coarse-grained, contain intraclasts, or well-preserved shallow- or open-marine microfauna.

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