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SUCCESSION OF PLEISTOCENE NON-MARINE SEDIMENTS CONTAINING MARINE FOSSILS, MLJET ISLAND, EASTERN ADRIATIC (CROATIA)

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Small areas of Pleistocene sands occurring on islands in the eastern Adriatic, Croatia, record environmental and depositional conditions during climate changes of that period. The Pleistocene deposits of the Island of Mljet located in the south-eastern Adriatic have been studied using mapping, logging, facies analysis, petrography, heavy minerals and fossil content. The studied sediments include modified deposits, aeolian deposits and fluvial deposits. Modified sediments originated from previously deposited sands and minor gravels which experienced pedogenic homogenisation. Aeolian deposits are represented by deflationary gravel, dune cross-stratified sands and low-angle laminated sands. Aeolian sands were mostly sourced from exposed, shallow-marine sands. Fluvial deposits include gravels reworked from the slope and colluvial sediments related to the carbonate bedrock, and recycled aeolian sands, which were deposited by high-gradient streams. Two tephra horizons represent former sand-grade volcaniclastic material reworked by streams, mixed with aeolian sand and deposited from river floods shortly after eruption and ash fall.

The studied succession includes major stratigraphic surfaces (=super bounding surfaces) related to processes of landscape stabilisation and stratigraphic gaps. The lower, modified part of the succession originated during an interglacial (or interstadial) period. Subsequent aeolian sands reflect the onset of a glacial period characterised by strong, cold winds, and an initial sea-level fall which resulted in the exposure of shallow-marine sands, making them a source for the aeolian sands. It is tentatively proposed that the base of the aeolian deposits corresponds to the onset of the Last Glacial period.

Key words: South-eastern Adriatic, Late Pleistocene, Mljet Island, aeolian sands, fluvial gravel, epiclastic tephra, provenance of sand.

Babić, Lj., Zupanič, J., Vidović, J., Razum, I. & Crnjaković, M.: Slijed pleistocenskih kopnenih sedimenata s morskim fosilima na otoku Mljetu, istočni Jadran (Hrvatska). Nat. Croat., Vol. 21, No. 2., 269–299, 2012, Zagreb.

Male pojave pleistocenskih pijesaka na otocima istočnoga Jadrana Hrvatske bilježe okolišne i taložne uvjete u vrijeme klimatskih promjena toga razdoblja. Pleistocenski sedimenti otoka Mljeta, koji je smješten u jugoistočnom Jadranu, proučeni su pomoću kartiranja, mjerenja stupova, analize faciesa, petrografije, teških minerala i fosila. Proučeni sedimenti obuhvaćaju modificirane taložine, eolske taložine i fluvijalne taložine. Modificirani sedimenti nastali su iz ranije taloženih pijesaka i manje šljunaka, koji su pedogenetski homogenizirani. Eolski sediment su deflacijski šljunak, križno-stratificirani pijesci dina i nisko-kutno laminirani pijesci. Eolski pijesci većinom potječu iz okopnjenih morskih pijesaka. Fluvijalni sedimenti uključuju šljunke riječno prerađene iz padinskih i koluvijalnih taložina vezanih za karbonatno gorje, te reciklirane eolske pijeske, koji su, jedni i drugi, taloženi iz struja visokoga gradijenta. Dva horizonta tefre predstavljaju raniji vulkanoklastični materijal pješčane veličine zrna, koji je, ubrzo nakon erupcije i padanja pepela, bio prerađen strujama, miješan s više ili manje eolskog pijeska i konačno istaložen pomoću riječnih poplava.

Proučeni slijed uključuje glavne stratigrafske plohe (=granične super-plohe) vezane za procese stabilizacije krajolika i stratigrafske praznine. Donji, modificirani dio proučenoga taložnog slijeda nastao je u vrijeme jednog interglacijala (ili interstadijala). Naredni eolski pijesci odražavaju početak jednog glacijalnog razdoblja označenog snažnim, hladnim vjetrovima, te početni pad morske razine koji je doveo do izlaganja plitkomorskih pijesaka i učinio ih tako izvorom za eolske pijeske. Provizorno se predlaže da se dno eolskih sedimenata razumije kao početak Zadnjega Glacijala.

Ključne riječi: jugoistočni Jadran, Mlađi Pleistocen, otok Mljet, eolski pijesci, riječni šljunci, epiklastična tefra, provenijencija pijeska.

INTRODUCTION

Aeolian sediments may derive from different sources including alluvial accumulations, shoreline deposits, shallow-marine sediments, glacial outwash deposits, as well as other settings deprived of vegetation. In the Mediterranean, there are widespread Pleistocene aeolian deposits the origin of which is related to specific climatic conditions which characterised that period. Along the eastern Adriatic coastal belt, Pleistocene aeolian deposits occupy smaller, isolated areas (MARKOVIĆ-MARJANOVIĆ, 1976, 1977; CREMASCHI, 1990a, 1990b; BOGNAR *et al.*, 1992; among others). They belong to two realms. One of them includes Istria and the north-eastern Adriatic islands such as Susak and Lošinj (Fig. 1). These areas represented a part of an extensive aeolian realm which included the margins of the Po plain and the northern part of the present-day Adriatic Sea and related coasts (CREMASCHI, 1990a, 1990b; MIKULČIĆ PAVLAKOVIĆ *et al.*, 2011; WACHA *et al.*, 2011). Relevant aeolian sediments derived from alluvial accumulations of the ancient Po plain which extended farther towards the SE than it does today. During the Last Glacial Maximum the river Po and its alluvium occupied the shallow, NW part of the present-day Adriatic which was at that time covered by land (GRUND, 1907; CREMASCHI, 1990b; CORREGGIARI *et al.*, 1996). Another aeolian realm of the E Adriatic includes islands of the SE Adriatic archipelago, such as Hvar, Vis and Mljet (Figs. 1, 2). The Pleistocene aeolian deposits of this realm are considered to have derived from exposed areas (presently submerged) located between present-day islands and the mainland during sea-level lowstand (MARKOVIĆ-MARJANOVIĆ, 1976, 1977; BOGNAR *et al.*, 1992; PAVELIĆ *et al.*, 2011). More specifically, it is considered that the aeolian sands of Mljet and Hvar islands derived from alluvial accumulations of rivers which drained the Dinaridic mainland chain (BOGNAR *et al.*, 1992; PAVELIĆ *et al.*, 2011). Interestingly, KRKALO & PENCINGER (1995) reported on the occurrence of foraminifera in Pleistocene sands of Mljet Island and considered these sands to be of a marine origin.

The purpose of this work is to provide more details on the character of Pleistocene sediments on Mljet Island and to discuss their depositional environments, as well as to resolve the aeolian versus marine controversy concerning their origin.

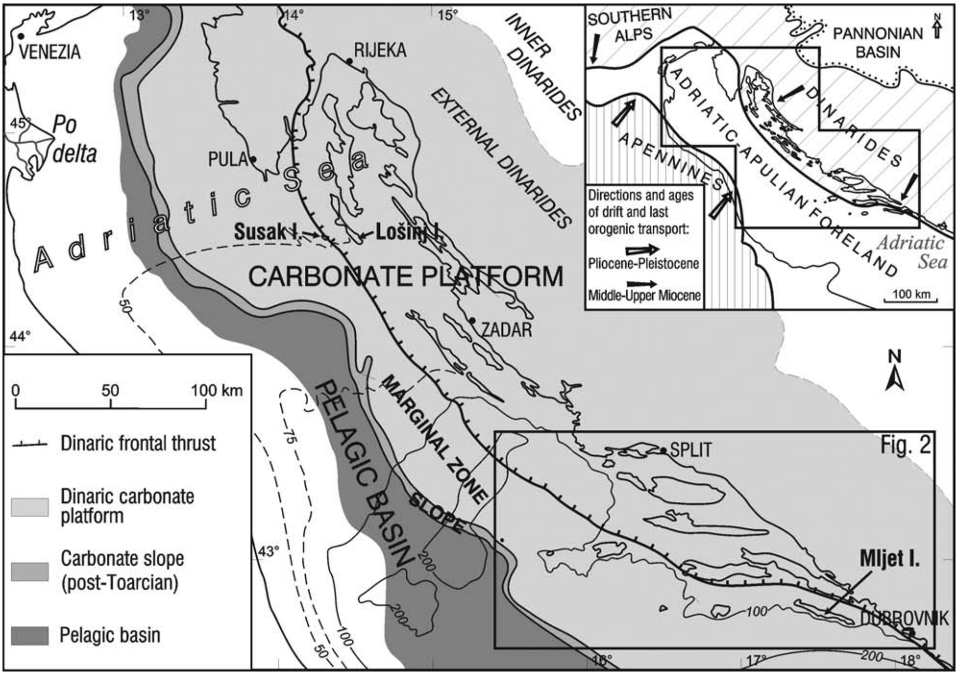


Fig. 1. Location of the Island of Mljet in the Adriatic Sea and within the area which was the marginal zone of the large, long-lasting, Mesozoic carbonate platform (simplified after GRANDIĆ *et al.*, 1999). Note the difference in depths between the shallow, northern part of the Adriatic Sea and its deeper, southern portion (topography simplified after PIGORINI, 1968). Also shown are the location of the Po delta and the Islands of Susak and Lošinj. For further explanation see text. Insert shows the distribution of larger tectonic units (simplified after BIGI *et al.*, 1990).

Also proposed is a reconstruction of the evolution of the area based on data from the studied succession. Furthermore, the sand accumulation on Mljet Island is discussed in terms of local, as well as regional Late Pleistocene palaeogeography of the SE Adriatic.

GEOLOGICAL SETTING AND PREVIOUS WORK

The Island of Mljet is one of numerous islands situated along the coastal belt of the Eastern Adriatic (Figs. 1, 2). It consists of Upper Jurassic and Cretaceous carbonates, and small patches of Quaternary deposits (KOROLIJA *et al.*, 1976; RAJIĆ *et al.*, 1982) (Fig. 3). The carbonates originated within large carbonate platforms which characterise the a major part of the Mesozoic sedimentary evolution of the area, and today make up the Outer Dinarides (VLAHOVIĆ *et al.*, 2005; KORBAR, 2009). Mljet Island is regarded to represent a part of an outer zone of a long-lasting Mesozoic carbonate platform (»Marginal Zone« of GRANDIĆ *et al.*, 1999) (Fig. 1). To the NE, this zone is bounded by the Main Dinaric frontal thrust, while its SW boundary is defined by a transition represented by slope deposits which connects

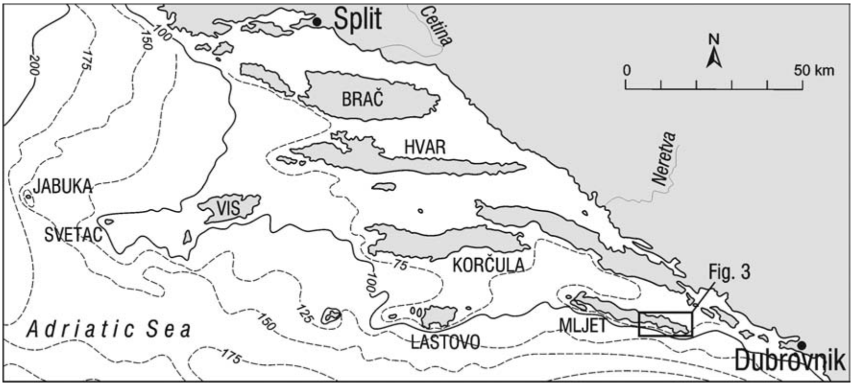


Fig. 2. SE Adriatic archipelago with location of Mljet Island (from PIGORINI, 1968).

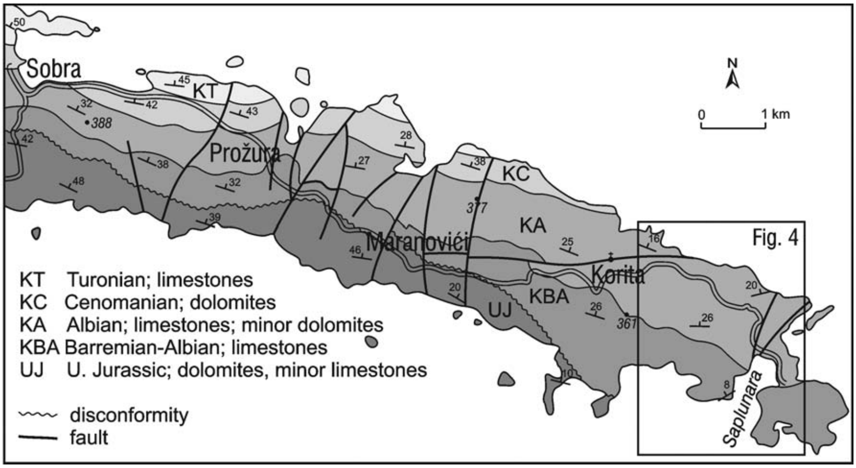


Fig. 3. Geological map of the eastern part of the Island of Mljet (after RAJIĆ *et al.*, 1982).

platform carbonates and post-Toarcian pelagic basin deposits (Fig. 1). The tectonic structure of the island is mainly the result of Tertiary compressional deformation.

Quaternary sands of E Mljet Island were mentioned by KOROLIJA *et al.* (1977). Later, BOGNAR *et al.* (1992) recognized obliquely stratified, sub-horizontal and massive sands in Pinjevica sand pit (Figs. 4, 5) and suggested their aeolian origin based on very good sorting, good roundness of sand particles and dull grain surface. They also reported on palaeosol horizons, as well as gravels deposited by torrents. BOGNAR *et al.* (1992) proposed that the sands had derived from fluvial deposits located between the present-day island and the mainland during the sea-level lowstand of the Late Würmian. In addition, these authors cited a late Holocene age of some of the sands based on the radiocarbon dating of a gastropod shell which provided an age of 3776-3363 years BC.

KRKALO & PENCINGER (1995) reported on a vitric tuff intercalation in the sands of the Pinjevica sand pit. They mentioned the presence of foraminifera in the sands

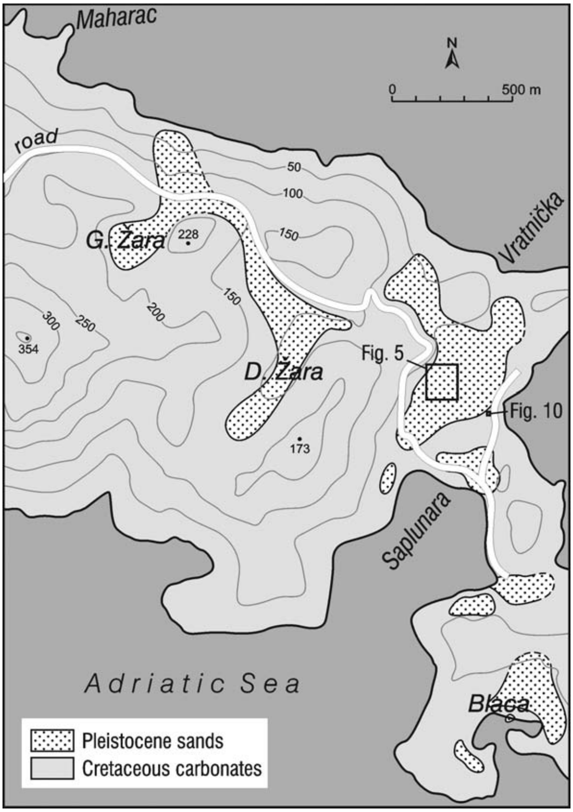
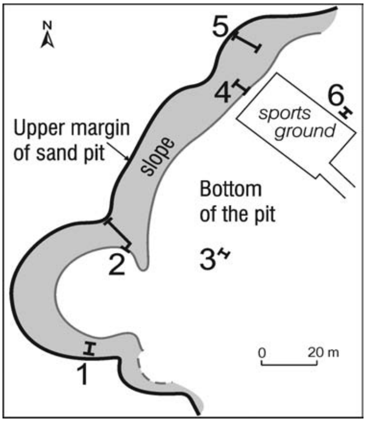


Fig. 4. Main areas of Pleistocene sands on the Island of Mljet. Very small sand patches, as well as smaller protrusions of carbonate basement within sand fields are not shown. Topography is simplified after Topographic map of the Republic of Croatia, 1:25000, Sheet Maranovići.

Fig. 5. Map of Pinjevica sand pit with location of measured sections. For location see Fig. 4.



and interpreted their deposition within a marine environment (based on unpublished report by Šćavničar, 1959). The mineralogy of the tuff layer has been described by Lugović *et al.* (2006).

STUDY AREA AND METHODS

Sand distribution in the E part of Mljet Island was mapped at scale 1:25000 (Fig. 3), while most of the data presented in this paper derives from observations made in Pinjevica sand pit (Figs. 4, 5). It is the same location from which all previous authors (Bognar *et al.*, 1992; Krkalo & Pencinger, 1995; Lugović *et al.*) derived their data. Several sections in this sand pit have been studied which cover parts of complete successions (Figs. 5, 6). A direct tracing between logs was not possible except (partly) for the top part of the succession (Unit G, Fig. 6). Since our visits in 1996 and 2000, the exposures changed for more extensive cover by loose sand, vegetation and waste material, as well as for modifications related to the construction of a sports playground.

The texture and composition of sands were studied on a limited number of samples as to compare our results to data presented by Bognar *et al.* (1992) who analysed 10 samples along the entire succession. Thin-sections of partly lithified sands were used for the study of particle types and cement. Carbonate content was calculated from the weight difference before and after treatment with 3% hydrochloric acid. The grain size was determined by wet sieving and using fractions >500 µm, 250–500 µm, 125–250 µm, 63–125 µm, 32–63 µm and <32 µm. Heavy and light minerals were separated following standard analytical procedures (MANGE & MAURER, 1992) using the 63–125 µm fraction and bromoform (density = 2,89 g/cm^3). Both the heavy and light mineral separates were embedded in Canada balsam and studied using polarising microscope.

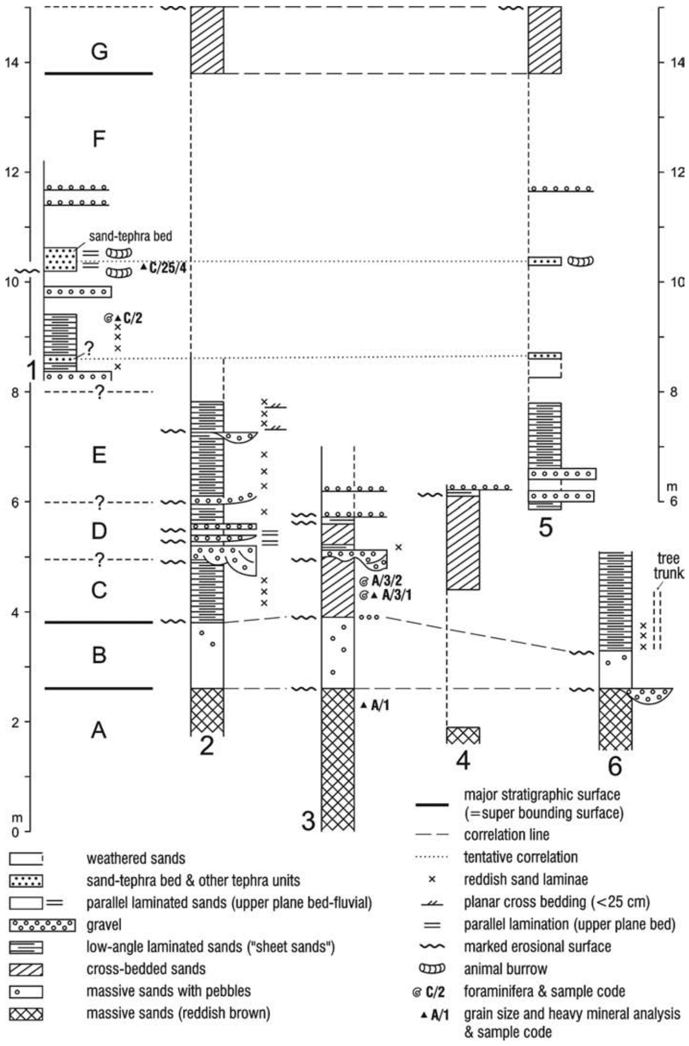


Fig. 6. Logs measured in Pinjevica sand pit. Aside from major stratigraphic surfaces indicated in the figure, there are presumably more surfaces of the same importance, which could not be identified reliably. Heavy mineral associations from 4 samples located in the logs are shown in Tab. 1. List of foraminifera in 3 samples marked in the logs is presented in Tab. 2. Location of logs in Fig. 5. For details see text.

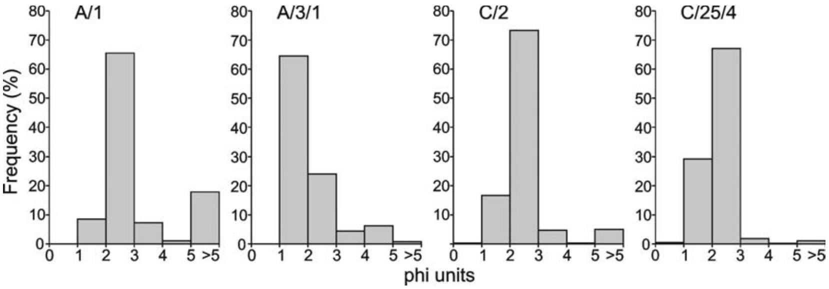


Fig. 7. Histograms showing grain-size frequency percentage by weight for 4 samples located in Fig. 6, Logs 1 and 3.

Foraminifera were studied from sand fractions 250–500 μm, 125–250 μm and 63–125 μm obtained by wet sieving, which were previously treated using trichloroethylene in order to separate foraminiferal tests from large amounts of sand (MURRAY, 2006). Identification of foraminiferal taxa follows the classifications of LOEBLICH & TAPPAN (1987) and CIMERMAN & LANGER (1991). Following the discussion by MURRAY (2006), the species name *Ammonia beccarii* is restricted to large forms typical of some localities in the Mediterranean. Foraminiferal frequencies are expressed in their number per 100 g of dry sediment.

AREAL DISTRIBUTION OF STUDIED SEDIMENTS

Pleistocene aeolian sands and associated deposits are common in the E part of the Island of Mljet where they occur in isolated fields covering a highly irregular topography of karstified Cretaceous carbonates including rather steep slopes (Fig. 4). In the Blaca Bay, the lithified sands extend below present sea level (Fig. 4). The sands occur up to about 170m above sea level (a.s.l.). In the Pinjevica sand pit, where most of the presented data derive from, the lowermost sediments occur at about 16m a.s.l. and their maximum thickness is about 15m.

PETROGRAPHY OF SANDS

The sands are fine to locally medium grained, and well to moderately sorted (Fig. 7) as already described by BOGNAR *et al.* (1992). Particles may be well rounded to angular. Non-carbonate particles make up 65–80% of the grains, and are represented by quartzite, chert (including radiolarian chert), quartz, mafic and ultramafic rocks, and subordinate metamorphic rocks and shales. Also included are plagioclase feldspars which are mostly fresh, as well as amphibole, pyroxene and epidote. Carbonate particles include limestone and rare dolomite clasts, as well as rare benthic foraminifera, corallinacean algae, mollusc debris and echinoid spines. The proportion of $CaCO_3$ amounts to 20–30%, except for one sample with only 2% $CaCO_3$ (Tab. 1). At some places, weathered sands include shells of smaller gastropods. Their occurrence seems to be related to Holocene plant rooting, however, a part of these gastropods might be autochthonous, a feature which deserves further study.

The particles usually display a thin, dark coating consisting of ferric oxides (Fig. 8). The sands may be cemented by mosaic, sparry calcite which is most commonly

Tab. 1. Heavy mineral (HM) distribution and CaCO3 content in 4 samples located in Fig. 6, Logs 1 and 3. Op, Opaque minerals; Lf, lithic fragments; Ch, Ms, Bt, chlorite, muscovite, biotite; OT, other transparent minerals; cpx, clinopyroxene; opx, orthopyroxene; am, amphibole; ep, epidote group; ky, kyanite; ol, olivine; gr, granate; sp, chromspinel; st, staurolite; un, unknown.

Sample code	HM= 100%				OT=100%										% $CaCO_3$
	Op	Lf	Ch, Ms, Bt	OT	cpx	opx	Am	ep	ky	ol	gr	sp	st	un	
C/25/4	24	6	1	69	50	22	13	7	+	2			+	4	20
C/2	10	17	2	71	31	23	31	10		+		+	+	3	21
A/3/1	22	16	2	59	46	14	31	2			1	1		4	30
A/1	13	9	1	77	43	30	23	1			+			3	2

encountered in facies of Cross-stratified sands and less in Low-angle laminated sands (both described below).

Heavy mineral associations (excluding opaque grains, lithic fragments, chlorite, muscovite and biotite), are dominated by clinopyroxene, orthopyroxene (mainly hypersthene), and amphibole (mainly green hornblende) (Tab. 1). They are followed by subordinate epidote group mineral grains, while other mineral species are rare. Some clinopyroxenes are probably augites of volcanic origin as suggested by their euhedral morphology. In comparison to data presented by BOGNAR *et al.* (1992), our results show a considerably higher proportion of pyroxene and considerably lower proportion of epidote. Light mineral fractions are dominated by quartz and lithic fragments with less feldspar grains, which is consistent with results presented by BOGNAR *et al.* (1992).

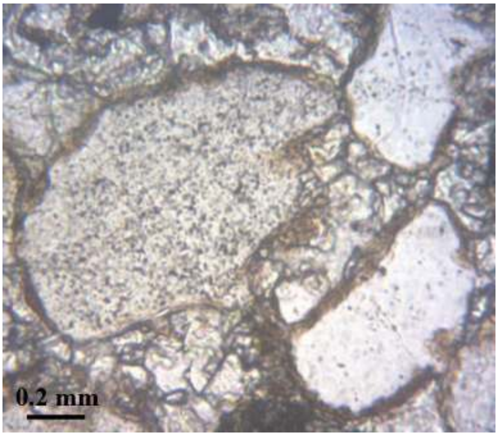


Fig. 8. Thin-section microphotograph displays a dark mineral coating on particles, typical for the studied aeolian sands, and mosaic calcite cement. Two light particles in the right are quartz grains, and in the left is a chert. Plane polarized light. Location in Fig. 6, Log 3, 4.5 m.

Tab. 2. List of foraminifera from 3 samples of aeolian sands located in Fig. 6, Logs 1 and 3.

	C/2	A/3/1	A/3/2
Quinqueloculina sp.		1	
Triloculina schreiberiana		1	
Sigmoilinita sp.		2	
Fissuripolymorphina williamsoni			2
Globigerina bulloides		4	
Globigerina sp.		10	
Orbulina universa		2	
Rosalina sp.		2	
Cibicides advenum		1	
Cibicides refulgens		1	
Ammonia beccarii	4	3	
Elphidium crispum		2	
Elphidium gerthi			1
Elphidium sp.	2		
TOTAL	6	29	3
No. of specimens/100g dry sand	2,5	8,7	2,6

FORAMINIFERA IN SANDS

The presence of smaller benthic foraminifera was recognised in a few sand horizons during field work, and 3 samples processed in the laboratory contained foraminifera (Tab. 2, Fig. 6). The sample richest in foraminifera contained 11 taxa in about 200g of sand, and foraminiferal frequency in the same sample amounts to 8.7 specimens in 100g of dry sediment. Table 2 shows that foraminiferal associations are dominated by smaller benthic forms, while planktonic foraminifera are locally common.

COMPOSITION OF GRAVELS

Particles in gravels as well as isolated coarse clasts occurring in some sands are dominantly lime mudstones and wackestones, rarely dolomites, identical to Lower Cretaceous carbonate types found in the surroundings.

DESCRIPTION AND INTERPRETATION OF FACIES

Massive sands

Massive sands form a >250 cm thick unit representing the lowermost part of the succession exposed in the pit (Fig. 6). These sands are reddish brown (Fig. 9) contrasting other sands which are brown to yellowish brown and locally grey. Rarely observed is a colour mottling. These sands differ from other sands also in a considerably lower proportion of $CaCO_3$ (2%; Tab. 1) and an increased proportion of <32 μm particles (Fig. 7). The unit seems to represent the basal segment of the

Fig. 9. Reddish-brown Massive sands (Unit A) in the lower part are overlain by Massive sands with pebbles (Unit B) which starts with a gravel-filled channel. Following are erosionally based Low-angle laminated sands (better shown in Fig. 17). Location in Fig. 6, Log 6, 1.5-3.5m. Shovel = 64cm.

Pleistocene succession of this area as might be suggested by closely situated exposure showing similar, light brown to reddish-brown sands filling karstification depressions and hollows in Cretaceous limestones (Fig. 10).

Fig. 10. Reddish brown sand in karstification depressions and hollows of Lower Cretaceous limestones. Hammer = 28cm. Location in Fig. 4.

Interpretation. Massive appearance and mottling may reflect pedogenic processes which were responsible for destruction of primary structures and sediment homogenisation. Pedogenic processes were responsible for dissolution of originally present carbonate particles and a lower $CaCO_3$ content compared to other sands. These processes may have also resulted in an increased content in <32 μm particles compared to other studied sands. Reddish colour is related to ferric oxides which were produced in an oxidising diagenetic environment, possibly in the vadose zone and/or in the zone of fluctuating ground water, where the iron may have derived from the alteration of iron-bearing minerals such as hornblende and biotite (WALKER, 1967). Original deposits could have been sands deposited by aeolian and/or stream-flow processes. The modification of original deposits may indicate a relatively warm climate, possibly with alternating longer, dry and shorter, wet conditions bearing a certain similarity with the Mediterranean-type climate.

Massive sands with pebbles

This facies is represented by a <1.4 m thick unit overlying the Massive sands facies described above along an even, sharp surface locally marked by smaller, partly channelized gravel bodies (Figs. 6 and 9). The unit consists of massive sands which locally display an irregular distribution of small pebbles (Figs. 9, 11 and 12), barely discernible mottling and a small relic of parallel lamination. Isolated, small pebbles are subangular to angular limestone clasts, mostly 0.5 to 5 cm in diameter. Within these sands there is a <0.5 m long, gently inclined train of isolated limestone clasts.

Fig. 11. Massive sands with pebbles (Unit B) in the lowermost part originated by pedogenic homogenisation of older sands. They are overlain by a sharp, flat, erosional surface marked by poorly visible, deflationary Gravel pavement (see also Fig. 12). Following are Cross-stratified sands (Unit C) of an aeolian dune. The upper part of the dune was removed by streams which subsequently deposited laterally accreted gravel and minor sand in shallow channels. The fluvial unit was followed by a sand dune which was largely removed by subsequent deflation and its remaining part was overlain by Low-angle laminated sands. These sands are erosionally overlain by fluvial gravel and minor sand. Their flat top surface probably resulted from deflation and was followed by Low-angle sands and by presumably another deflationary gravel unit (=Gravel pavement facies). Lower cross-stratified unit is 1m thick.

Fig. 12. Detail of Fig. 11. Deflationary gravel pavement represented by a discontinuous layer of pebbles is situated between Massive sands with pebbles (Unit B) below and Cross-stratified sands (Unit C) above. Location in Fig. 6, Log 3, 3.9m.

Interpretation. The sharp, planar basal surface was probably produced by deflation. The process may have occurred down to the water table or to within the capillary fringe of the water table, as has been inferred for many examples occurring in aeolian systems and is known as the »Stokes surface« (STOKES, 1968; FRYBERGER *et al.*, 1988; KOCUREK *et al.*, 1991; MOUNTNEY, 2006a; review in MOUNTNEY, 2006b).

Massive appearance, scattered pebbles and probable mottling reflect pedogenic processes which involved previously deposited sands and minor gravels. Inferred vegetation cover and overall yellowish-brown colour contrasting the reddish-brown underlying unit (Massive sands described above) suggest wetter conditions during modification processes. Original deposits were partly fluvial in origin as suggested by relics of gravel-filled channels and obliquely aligned pebbles of probable channel wall. Their origin is related to rain storms and related floods which brought in carbonate detritus from neighbouring carbonate slopes, as well as sands eroded from previous aeolian sands (see the Gravel-sand facies described below). Another part of this facies may have been produced by modification of previous aeolian sands.

Gravel pavements

This facies consists of erosionally based, one- to few-pebble thick, sheet-like units. They may also be represented by trains of isolated limestone pebbles stretching for 0.5 to a few metres (Figs. 6 and 12).

Interpretation. Thin, sheet-like gravel bodies and isolated pebble trains which overly a planar, erosional surface were produced as lags by deflation process which removed sand and left behind pebbles. It means that originally, there must have been a gravel-bearing facies such as the Massive sands with pebbles (described above) and/or the alluvial Gravel-sand facies (described below). Hence, previous, relatively wet conditions were replaced by a dry climate with no vegetation and no sand accumulation. The even deflationary surface implies the influence of a high ground water level which restricts the depth of sand removal as has been interpreted for similar coarse-grained units occurring in aeolian formations (reviews in KOCUREK, 1996 and MOUNTNEY, 2006b; examples in RODRIGUEZ-LOPEZ *et al.*, 2010). Poorly exposed younger parts of the studied succession (Fig. 6) include several <20 cm thick gravel sheets which might represent either deflation lags or fluvial gravel sheets.

Cross-stratified sands

The basal surface of this facies is flat, erosional and sometimes marked by the Gravel pavement facies described above (Figs. 11 and 12). The facies includes <1.5 m thick units showing foresets inclined <30° and directed between azimuths of 180° and 220°.

The cross-bedded units show a tangential basal contact which sometimes assumes a very gentle asymptotic geometry (Fig. 13). Rarely observed are intercalations of downward pinching-out lamination. The foresets include truncation surfaces (=reactivation surfaces) inclined at slightly lower angle compared to the foresets. A close inspection of these sands reveals the presence of smaller benthic foraminifera which are more numerous in some laminae.

The exposures commonly display »sandy stalactites« originated by washing out of loose sands. However, there are rare, vertical, cylindrical forms, which are less than 10 cm long and about 0.6 cm in diameter, consisting of more indurated sand probably representing rhizoliths. Also occurring are recent, vertical rhizoliths up to 1m long which should not be mistaken for fossil ones. Irregularly distributed, lithified portions of cross-beds weather out in positive relief from the exposures and show smaller, dip-parallel ridges and grooves.

The cross-stratified unit in Section 4 (Figs. 5 and 6) has been truncated by a steeply inclined surface first covered by massive sand including scattered limestone pebbles and subsequently, by an onlapping, concave-upward complex of sands showing various dip directions (Fig. 14).

Interpretation. The features of the cross-stratified units are regarded to reflect deposition from migrating aeolian dunes. In the case of alternating tangential laminae and downward pinching-out laminae, the former probably resulted from the grainfall process and wind ripple migration (in the middle-upper parts of the foresets), while the later represent downward ending grainflow tongues. These features are typical of aeolian dunes (HUNTER, 1977; reviews in KOCUREK, 1996; MOUNTNEY, 2006b). Reactivation surfaces originated by wind erosion (deflation) of the dune slipface and renewed dune progradation.

Similar foreset dip directions in different sections and at different heights of the studied succession suggest a general direction of migration of the dunes towards SSW as already reported by BOGNAR *et al*. (1992). This direction parallels the NNE-SSW-trending mountain slope flanking the depositional area (Fig. 4), and the wind directions may have been influenced by local topography. Hence, the primary winds might have come from the Dinaric mountains located to the NE.

The erosive, generally flat, basal surface of the aeolian cross-stratified units, which is locally marked by a deflationary gravel facies (Gravel pavements), reflects deflation of underlying deposits, probably down to the water table. This might be regarded as a second example of the »Stokes surface« (STOKES, 1968; FRYBERGER *et al*., 1988; MOUNTNEY, 2006a; review in MOUNTNEY, 2006b) occurring in the studied succession (further discussed in section on sedimentary evolution).

The dune migration above a deflationary surface reflects strong winds combined with a high supply of sand, as well as related, relatively low water-table which may have been quasi-static during the relevant period as described from other aeolian systems (review in MOUNTNEY, 2006b). If any vegetation existed on the dunes, it must have been very sparse due to a relatively dry climate, strong winds and a low water table. Its need for water must have been satisfied by very sparse rainfall, and possibly by dew and/or frost and snow thawing. Dip-parallel, irregular ridges and grooves characterising cemented parts of the foresets might reflect paths of water moving down the inclined bedding.

Fig. 13. Cross-stratified sands. Note asymptotic geometry of the lower part of the dune. Log 4: 4.25-5.8m. Visible part of the shovel is 40cm long.

The steep surface truncating the cross-stratified unit in Section 4 could have resulted from a deep scouring of the aeolian dune by a stream. The sand including scattered pebbles covering this surface and subsequent, concave-upward sands reflect a sliding down the channel wall and aeolian infill respectively, which repaired the damage produced by the stream.

Low-angle laminated sands

Observed thickness of Low-angle laminated sands may attain about 2 m, and this facies possibly constitutes even thicker units within poorly exposed parts of the studied succession (units E and F in Fig. 6). The facies consists of laminae sets, 2 to 20 cm thick, which are commonly separated by truncation, onlap and downlap bounding surfaces in various combinations (Figs. 15 to 17). Laminae sets may pinch out completely along these surfaces. The laminae within a set may be either horizontal, gently inclined (<10°), gently diverging-converging, slightly irregular, and individual laminae may pinch out. Besides predominating fine to medium sand, individual laminae of medium to coarse sand pinching out laterally also occur. The surfaces bounding the laminae sets are commonly marked by a reddish brown

Fig. 14. Oblique surface truncating the aeolian dune on the left presumably resulted from stream erosion. The surface is covered by sand containing scattered pebbles (indicated by dots and circles), while the concave-upward aeolian sand complex has filled the remaining depression. The dune unit is 1.8m thick and is located in Fig. 6, Log 4.

Fig. 15. Low-angle laminated sands. Individual reddish sand laminae (the colour is barely visible) protrude from the weathered exposure surface. A roughly parallel distribution of these laminae predominates, and in the left, such laminae are oblique, unconformable and may merge together. They separate thin sand units whose laminated structure is not visible. Spatula = 22cm. Location in Fig. 6, Log 2, 6.7m.

Fig. 16. Dark (reddish brown to grey) clay unit in the middle, presumably representing a tephra, is underlain by truncated Low-angle laminated sands and is also onlapped by this same facies. Thin reddish sand laminae may be discontinuous, may laterally disappear and may also be represented by small relics. In the upper left, there is a more regularly parallel laminated sand variant of this facies. Marker = 13.5cm. Location in Fig. 6, Log 1, 8.5m.

Fig. 17. Massive sands with pebbles (Unit B) is truncated by an erosional surface and overlain by a variant of Low-angle laminated sands represented by two units of parallel laminated sands bounded by comparatively thicker reddish sand laminae. Laminated sand units show an overall wavy geometry. The lower unit pinches out to the left where two reddish laminae merge together. The laminae of the upper unit first downlap reddish sand lamina to the right, and subsequently parallel the reddish lamina base. For further explanation see text. Location in Fig. 6, Log 6, 3-3.8m.

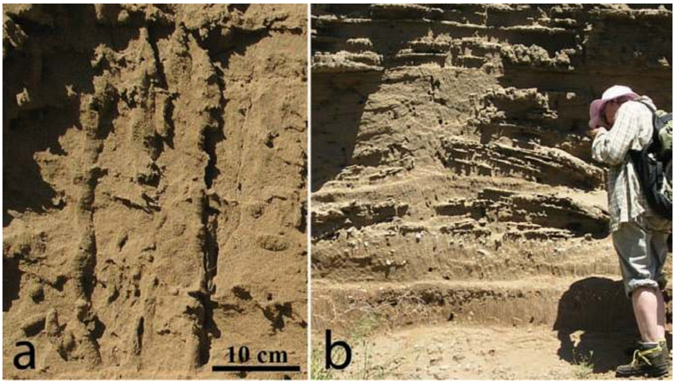


Fig. 18. Low-angle laminated sands. **a,** Rhizoliths. Location in Fig. 6, Log 2, 9m. **b,** Vertical body of structureless sand in the middle presumably represents a tree trunk. It is surrounded and overlain by Low-angle laminated sands facies which shows a gentle upward bending. Underlying are Massive sands with pebbles (Unit B) and still lower, reddish Massive sands (Unit A). Location in Fig. 6, Log 6. The outcrop has recently been destroyed.

lamina (becoming intensely red when wetted), whose colour contrasts the yellowish brown colour of surrounding sands. These laminae may overlay truncated laminae sets or parallel underlying lamination. Reddish-brown laminae are 0.2 to 1.5 cm thick and are commonly better indurated compared to the sands within laminae sets. They are commonly corrugated, may be discontinuous, and locally represented by aligned, 1 to 2 cm wide pieces some of which show soft-sediment bending. The sand of this lamina type is slightly enriched in finer grade particles compared to other sands.

Rarely observed are 15–20 cm thick intercalations of cross-laminated sands.

Bioturbation is rather common. Most common are vertical tubes/cylinders <60 cm long and 2 to 3 cm in diameter, which may be better indurated compared to surrounding sand (Fig. 18a). At Section 6 (Fig. 6, Log 6) there is a vertical, presumably cylindrical body consisting of structureless sand about 1.10 m long and about 20 cm in diameter (Fig. 18b). Surrounding lamination shows a gentle upward bending close to the feature. Partly submerged, cylindrical bodies of indurated sand observed in Blaca Bay (Fig. 19) are regarded to belong to this facies.

A peculiar facies variant here included in Low-angle sands is represented by onlapping and/or pinching out units of wavy, parallel laminated sands (fine laminae) lacking bioturbation, which are bounded by individual reddish laminae described above (Fig. 17). They mainly conform to the description of Low-angle facies presented above; however, they lack bioturbation and display fine lamination which may be wavy.

The particle composition of these sands is similar to that of Cross-stratified sands, as is the heavy mineral association (Tab. 1) and they also contain foraminifera (Tab. 2).

Interpretation. These sands show features in common with »low-angle aeolian sand sheet deposits« of FRYBERGER *et al.* (1979), who described recent examples and

Fig. 19. Erect, cylindrical bodies (12-18cm in diameter) are fossil roots or stumps. The outcrops probably correspond to Low-angle laminated sands facies described from Pinjevica sand pit. Blaca Bay. Location in Fig. 4.

compared them to ancient counterparts. The facies has been described from many aeolian formations (e.g. AHLBRANDT & FRYBERGER, 1981; KOCUREK, 1981; KOCUREK & NIELSON, 1986; VEIGA *et al*., 2002; MOUNTNEY & THOMPSON, 2002). After FRYBERGER *et al*. (1979), AHLBRANDT & FRYBERGER (1981) and other authors, several processes are responsible for the origin of this facies and they are reviewed here as related to the features observed in the studied sands. Erosional surfaces resulted from deflation and some of them might reflect erosion down to the water table. Fine, parallel laminae probably indicate a deposition by grainfall or possibly wind ripples. The gentle inclination of laminae may originate from deposition above inclined erosional or depositional surfaces. Besides, plants may cause deposition on uneven surfaces surrounding them. Coarser grained laminae may have originated from deflation, while some pinch-out laminae could have been produced by wind ripples (translatent climbing strata of HUNTER, 1977). Downlapping lamination reflects individual high-index ripple progradation. Inclined erosional surfaces and pinching-out laminae sets reflect an irregular topography of the depositional area. Corrugated and soft-sediment deformed reddish laminae indicate dampened sediment. Corrugated laminae might represent raindrop or hail imprints, however, they could also have originated by melting of the snow cover (»pitted surfaces« of AHLBRANDT & ANDREWS, 1978) or be related to the cover of microphytes (e.g. KOCUREK, 1981). Some examples of lateral discontinuities of reddish laminae resulted from bioturbation. A shallow, probably fluctuating water table is indicated by locally abundant vertical tubes presumably representing rhizoliths (review in EKDALE *et al*., 1984). The vertical body of structureless sand (Fig. 18b) may represent a former tree trunk probably rooted in underlying Massive sands with pebbles, while indurated, cylindrical bodies from Blaca Bay are root traces or traces of tree trunks or stumps (Fig. 19). These features suggest the presence of locally dense vegetation. Intercalations of thin cross-laminated sands probably reflect occasional migration of smaller aeolian dunes, however, some of these structures may have alternatively been deposited by streams.

In general, the depositional setting of Low-angle laminated sands was dominantly characterised by both deposition and erosion by wind, while from time to time it experienced damp conditions. During short, intermittent intervals the area, or part of it, was possibly flooded. The flooding intervals might have been related to fluvial activity (otherwise responsible for the origin of Gravel-sand facies described below) and related rises in water table, however, wetting and dampening may also be related to snow thawing. The vegetation was generally sparse and locally denser. Local lithification of these sands possibly reflects a shallow water-table which closely followed the rising depositional surface.

A specific variant of sands included in this facies is represented by sets of wavy, finely laminated sands lacking bioturbation but showing onlap, pinching out and bounding reddish laminae (Fig. 17), as other sands of the Low-angle facies, possibly originated from alternating dry intervals of sandfall deposition (laminae sets), and wet intervals without deposition. This facies could represent a dune apron.

Gravel-sand facies

This facies occurs either as individual gravel units, gravel and sand couplets, sand units, or as a larger, complex unit including several gravel and sand segments. Individual units display erosional bases including channels up to 0.4 m deep (Fig. 11, Figs. 20 to 22). Two channels are oriented 240°–60° and 275°–95°, respectively. Channels are filled either by gravel (majority of very small channels) or by laterally accreted gravel and sand. A channel fill in Section 2 (Fig. 5), includes a boulder-sized clast consisting of alternating gravel and sand. Gravels also occur as sheets up to 14m wide, as well as concave upward lenses, both features observed in a section approximately perpendicular to transport direction deduced from channel elongation. Imbrication of clasts in gravels is rarely observed, is laterally restricted and dipping NW. The clasts in the gravels vary in size between several mm and 30 cm, with most common sizes between 1.5 cm and 4 cm. They are angular to subangular limestones, and very rare dolomites and clasts of poorly indurated sand. The lateral extent of sand units is larger than that of gravels, possibly twice or more, however, they are often truncated by overlying gravels. Sands are typically characterised by coarse, parallel lamination. The single observed complex unit is 2 m thick and comprises several successive, simple units, each of them erosively overlying the previous one, in which the sand divisions are commonly represented

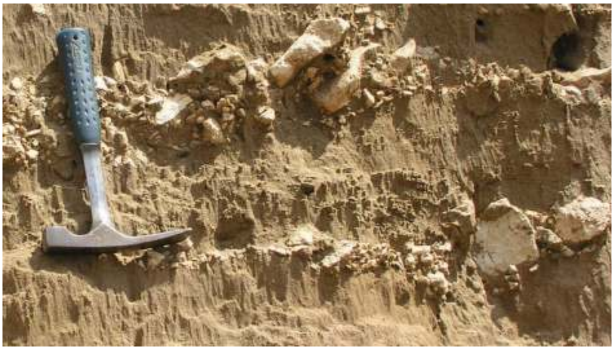


Fig. 20. Gravel-sand facies. Erosionally based couplets of gravel and sand. The lower gravel unit pinches out to the left, toward the margin of a shallow channel. The upper gravel unit shows imbricate clasts. Hammer = 28cm. Location: laterally to Log 2 in Fig. 6.

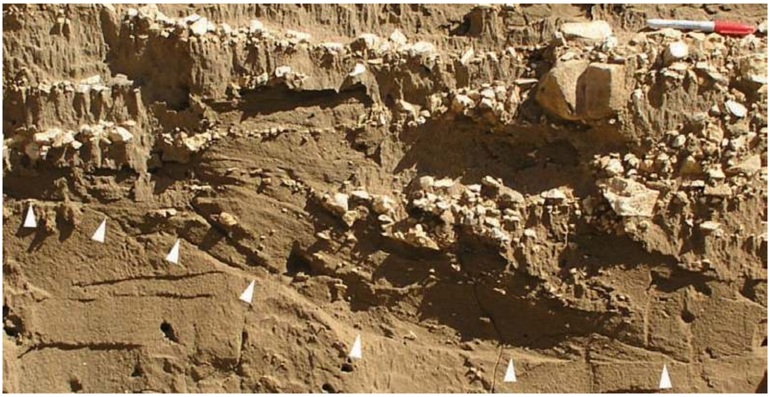


Fig. 21. Gravel-sand facies. Several, erosionally based gravel-sand couplets. Erosional surface (arrowed) is the base of the complex (multi-story) fluvial body overlying Low-angle laminated sands facies. Erosional depression (channel) is infilled by coarsely laminated sand, as well as gravel. Marker = 13.5cm. Location: Fig. 6, Log 2, about 5.5m.

Fig. 22. Successive, erosionally based gravel-sand couplets (Gravel-sand facies) consist of gravel (locally showing imbrication dipping inside left) and parallel laminated sand (upper plane bed). They represent the lower part of a composite (multi-story) fluvial body incised (arrows) into the facies of Low-angle laminated sands. In this location the body starts with parallel laminated sand. Light part of marker = 8.5cm. Location: Fig. 6, Log 2, 4.7-5.5m.

by erosional remnants (Figs. 20 to 22). Gravels and sands may be involved in soft-sediment deformations by which the gravels are depressed into underlying sands.

As already mentioned above, close to Section 4 (Fig. 5 and Fig. 6, Log 4) there is a prominent, oblique truncation surface, 1.8m deep, cutting aeolian sands. It is covered by sand including scattered limestone pebbles, and onlapped by aeolian sands (Fig. 14).

Interpretation. Features of this facies reflect erosion and deposition related to high-velocity water flows. The orientation of channels (240°-60° and 275°-95°) and gravel imbrication (dipping NW), together with lithoclast types in gravels and a short-distance transport of dominantly angular limestone clasts, imply flow directions between ENE and SE, as well as detritus sources on carbonate bedrock slopes located to the W. The flows included coarse-grained detritus from the carbonate highs, as well as eroded, remobilised aeolian sand from the sand-covered area. Aeolian sand was very vulnerable to erosion by rapid, high-gradient stream flows and the largest part of the stream-flow sands represents recycled aeolian sand.

The streams may have scoured into both the fluvial and aeolian sediments and deposited their load down-valley in both channels and as sheet-like bodies. The boulder consisting of sand and gravel fell from the undermined channel wall. The prominent, steep truncation surface close to Section 4 (Fig. 14) may represent a wall of an at least 1.8m deep fluvial channel which was first covered by sand and rare pebbles from the channel wall, while the damage was subsequently repaired by deposition of aeolian sands. The character of the flows is indicated both by the coarseness of carbonate lithoclasts and by the upper plane bed regime during sand deposition. The flows are comparable to those related to low-sinuosity fluvial systems characterised by flash floods, which resulted from heavy rains and rainstorms (e.g. MIALL, 1996). Consecutive flood events may have followed close to one another thus generating larger, multi-story (complex) bodies (Figs. 20 to 22). They have been associated to river valleys, a situation similar to those described from aeolian settings (DOTT *et al.*, 1986; LANGFORD, 1989; LANGFORD & CHEN, 1989 among others).

Soft sediment deformations mentioned above originated by liquefaction and occurred closely after rapid deposition of loosely packed sands and gravels, in water-saturated conditions of the two sediment types (POSTMA, 1983). Similar features have been described and amply illustrated from Mid-Cretaceous aeolian-fluvial deposits of E Iberia (RODRIGUEZ-LOPEZ *et al.*, 2010).

Sand-tephra bed and other tephra units

The tephra layer reported previously (KRKALO & PENCINGER, 1995; LUGOVIĆ *et al.*, 2006) is yellow clayey sediment. However, it does not occur as a separate bed but actually forms a part of a bed consisting of tephra and sand. It is based by a sharp erosional surface and is internally characterised by coarse parallel lamination. The distribution of sand and tephra components in the bed varies along the exposure at short distances. Tephra laminae may either be intercalated in sand or represent smaller or major parts of the bed at different heights above the bed base (Figs. 23 to 25). Tubular traces, 1 to 1.3 cm in diameter, winding in different directions, occur throughout the bed, and also pass through the lower bed surface into the underlying sand (Fig. 25). Exposed segments of the traces are <10 cm long. Their

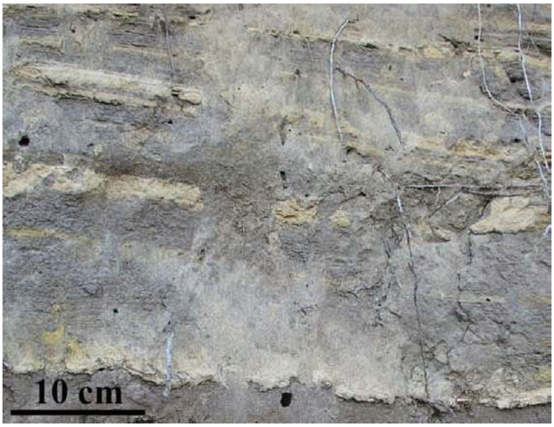


Fig. 23. Sharply based Sand-tephra bed displays parallel lamination (upper plane bed) with alternating bands and laminae characterised by variable proportions of tephra (yellow) and sand. Note intense bioturbation. Underlying (bottom of the figure) are weathered sands. Location: Fig. 6, Log 1, 10.5m. Marker = 13.5cm.

Fig. 24. Aeolian sand in the lower part is overlain by a Sand-tephra bed dominated by yellow tephra. The greyish-yellow band in its lower part consists of a sand-tephra mixture. Darker patches in the tephra are burrows filled by the same mixture. Overlying brown sand displays burrows mainly filled by yellow tephra. Metal part of spatula is 11cm long. Fig. 6, Log 1, 10.4m.

infill consists either of sand, tephra, or a back-fill (»Spreite«) type which includes both sand and yellow tephra. One and the same trace may contain different types of sediment fill. Intense bioturbation is common.

Section 5 (Fig. 6, Log 5) includes two poorly exposed layers of weathered, yellow clay, 10 to 20 cm thick (Fig. 26) which include tubular traces identical to those observed in the Sand-tephra bed described above and are considered to represent tephras. These tephras seem to be associated with sand in a similar way like in the Sand-tephra bed.

Section 1 includes an erosionally based, weathered reddish brown to gray clay layer, 3 to 5cm thick (Fig. 6, Log 1, 8.5 m and Fig. 16) which possibly represents an altered tephra layer.

Interpretation. Erosional base and coarse parallel lamination of the Sand-tephra bed suggest the erosional power of the flow and upper-stage plane bed regime during deposition. Such a sudden, vigorous surge is comparable to what is known as flash flood (review in MIALL, 1996). The process started with a heavy rainfall or rainstorm and included stream erosion and subsequent deposition of a sheetsand unit in the topographic low. Eroded sediments consisted of remobilised aeolian sand (possibly also some previous fluvial sand) and volcaniclastic material, the latter, at that time, consisting of sand-grade particles of volcanic glass which mantled the topography. The two types of sand-grade material were collected by streams, transported and redeposited together by one and the same process which resulted in a single bed. Hence, the tephra is epiclastic in character and derived from previously deposited volcanic ash produced by a Plinian-type eruption. The ash fall must have occurred only slightly before its redeposition, because original volcanic glass particles, otherwise known to alter quickly, must have been present at that time. This is in accordance with results of a study on Taupo 1800a pumice, where MANVILLE *et al.* (2002) suggested that cool pumice clasts, when sufficiently water-logged, may behave hydrodynamically as quartzo-feldspathic material.

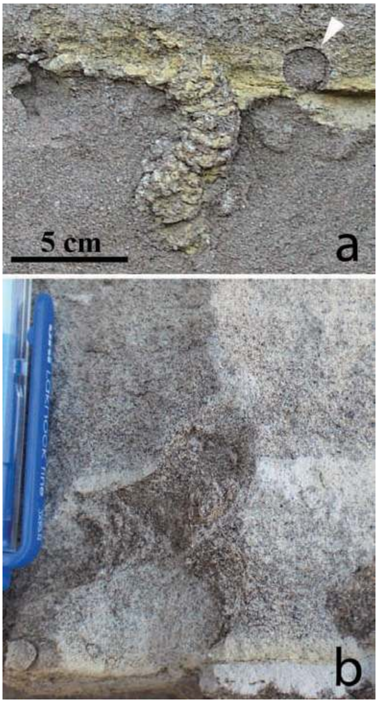


Fig. 25. Sand-tephra bed. **a,** Yellow tephra is concentrated in the basal part of the bed. Animal burrow (Spreite) at the base consists of yellow tephra and grey sand. Arrow points to a circular section of a sand-filled burrow. Location: Fig. 6, Log 1, 10.4m. Marker = 13.5cm. **b,** Lower part of Sand-tephra bed showing parallel lamination with varying proportions of tephra (light) and sand. Spreite-type burrows consist of both the sand and tephra. Pen clip = 4cm. Location: Fig. 6, Log 1, 10.5m.

Fig. 26. Poorly exposed yellow tephra is underlain and overlain by weathered sands, probably Low-angle laminated sands facies. Spatula = 22cm. Location: Fig. 6, Log 5, 8.6 m.

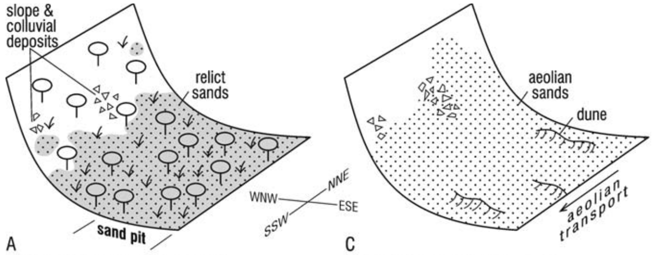
The burrows were produced within grainy material apart from its local particle composition which ranged from purely non-volcaniclastic sand to purely volcaniclastic sand and including all combinations of the two, because the fabric of the burrow fills indicates the substrate of a uniform »looseground« character (term »looseground« after BROMLEY, 1996). The burrows must have been produced by an animal in wet sediment at a time when the surface was covered by water which probably persisted for some time after the flooding occurred. The present-day mineralogy of the tephra has been proposed to indicate wet conditions (LUGOVIĆ *at al.*, 2006) which might have been present shortly after deposition or somewhat later.

Two tephra layers in Section 5 (Fig. 6, Log 5 and Fig. 26) are similar to the tephra of the Sand-tephra bed in their yellow colour, animal burrow types related to the looseground substrate and inferred wet conditions. It is possible that these tephras were also deposited together with sand in the way described for the Sand-tephra bed. If the weathered, reddish brown to gray clay layer in Section 1 represents an altered tephra layer (Fig. 6, Log 1, 8.5m and Fig. 16), it is also epiclastic in origin and deposited by a sheetflood, which is consistent with the erosional character of its base. This layer and the Sand-tephra bed in Section 1 are possible correlatives of the two tephras in Section 5 (Fig. 6).

EVOLUTION OF THE STUDY AREA AND STRATIGRAPHY

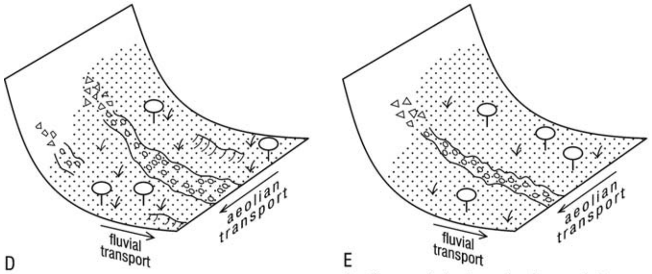
The earliest history related to the studied sediments in the sand pit has been obscured by pedogenic homogenisation of older sands now represented by Unit A (Fig. 6). A part of these sands was probably originally deposited by aeolian, while another part might be of primary fluvial origin. The modification processes occurred under a relatively warm climate and fluctuating water-table and ultimately led to landscape stabilization (TALBOT, 1959; Fig. 27A). After a deflation period, the top of these sands was covered by the sand of Unit B, and the A/B bounding surface became a major stratigraphic surface (Fig. 6). Sands of Unit A were possibly also preserved as fills of karstification depressions and hollows of the Lower Cretaceous carbonate basement observed in the close vicinity (Fig. 10).

Unit B also represents pedogenically modified original facies (aeolian and fluvial) under comparatively wetter climate and the influence of a relatively higher average



A
Pedogenic modification of older Pleistocene sands.
(Interglacial period)

C
Aeolian dunes and sandsheets.
Vegetation sparse or none.
(Onset of glacial period)



D
Aeolian sand sheets and dunes, ephemeral streams. Fluvial recycling of colluvial gravels and aeolian sands. Vegetation sparse to dense.
(Glacial period)

E
Aeolian sand sheets and ephemeral streams. Fluvial recycling of colluvial gravels and aeolian sands. Vegetation sparse to dense.
(Glacial period)

Fig. 27. Schematic diagrams presenting main environmental features related to units A, C, D and E of the Pinjevica sand pit. Dune types are not implied. Not to scale. For details see text.

water table in comparison to Unit A. Thus, the A/B surface is comparable to a »super bounding surface« or »super surface« of aeolian stratigraphy (review in MOUNTNEY, 2006b) as it separates genetic packages originating under different climates and marks an important hiatus.

The end of Unit B is also marked by landscape stabilisation controlled by the climate. The flat B/C boundary is a deflationary surface, marks a hiatus and also represents a major bounding surface. While the units below this surface reflect extremely low rates of sand accretion with intervals of cut off from the sources of sand and erosion, the subsequent Unit C originated by fundamentally different conditions characterised by considerable sand accumulation, strong winds and a lower water table. The relevant bounding surface therefore is also a major stratigraphic surface (e.g. TALBOT, 1959; KOCUREK, 1981), and a super bounding surface in terms of aeolian stratigraphy (review in MOUNTNEY, 2006b).

The B/C bounding surface discussed above may be regarded to represent a boundary between sedimentary products of an interglacial (or interstadial) and a glacial period of the Pleistocene. Namely, modifications observed in Units A and B likely occurred under conditions of an overall sea-level highstand, when the supply of sand was reduced and the climate was relatively warm, which corresponds to an interglacial period. The original deposits of Units A and B may have been produced either during the same interglacial period or (at least Unit A) even during a previous glacial period. The occurrence of marine fossils in the aeolian Unit C (and higher upwards) suggests a deflation of near-by marine sands, which implies a lowering of the sea-level related to the onset of a glacial period (Figs. 27C and 28). Such a tentative evolution is in accordance with the correlation existing between onset of glaciation, sea-level fall and increase in aeolian activity responsible for redeposition of near-by marine sands, described from the Mediterranean realm (Fornós *et al.*, 2009; Andreucci *et al.*, 2010). Pleistocene sands of the SE Adriatic islands are regarded to be Late Pleistocene (Würmian and Late Würmian) in age (Marković-Marjanović, 1976, 1977; Bognar *et al.*, 1992), although a precise dating has not been provided as yet. In the absence of a more precise dating, a further discussion on the age of the relevant sands could lead to over-interpretation. However, we suggest that it may be reasonable to adopt the Last Glacial interval as the period when deposition of the aeolian sands of Unit C started. Namely, the sands of this period may be envisaged as preferentially preserved compared to older Pleistocene sands. Data from Mallorca indicates that there was a rapid sea-level drop to about –15m around 77000 years (Dorale *et al.*, 2010) and comparable conditions are regarded to have caused the exposure of shallow-marine sands, making them a source of material for building dune systems on Sardinia at that time, i.e. at the onset of the Last Glacial period (=beginning of Marine Isotope Stage 4; Andreucci *et al.*, 2010). It is proposed that results of the same processes are recorded in the studied Mljet succession, and likely occurred at the same time. A variant interpretation could be based on the different character of Unit B versus Unit A, where Unit B shows some traces of original facies (discussed above). Hence, Unit B could originally represent the result of an earliest interval of climate deterioration, and the A/B bounding surface (instead of the B/C surface) be regarded as reflecting the onset of the glacial period (Fig. 6).

Aeolian deposition and cold, strong winds inferred to correspond to the onset of a glacial period (Unit C), presumably the Last Glacial, subsequently varied to alternating aeolian deposition and deposition from high-gradient streams (Unit D;

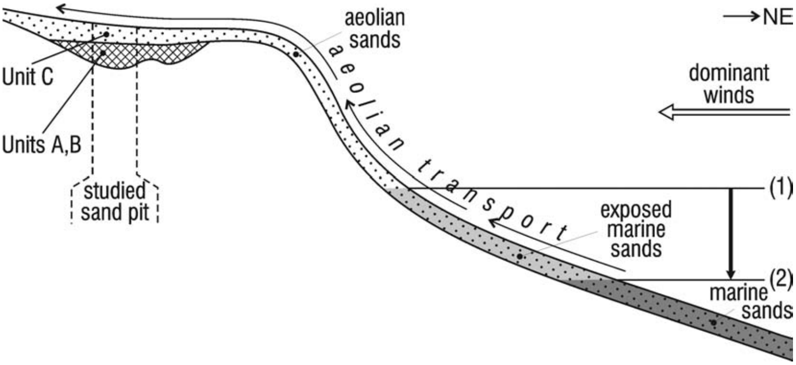


Fig. 28. Conceptual diagram showing the situation during the deposition of Unit C. (1) Sea-level during interglacial conditions related to the modification processes which led to the origin of units A and B. (2) Sea-level after the initial drop at the onset of the glacial period (presumably last glacial period), which led to the exposure of marine sands, their transport to the SW by strong NE winds and deposition. Not to scale. For details see text.

Figs. 6 and 27D). They reflect an alternation of relatively dry climate, and intermittent rainstorms and ground-water rises. The streams usually included detritus of two types: (1) coarse carbonate debris eroded from the slope, talus and colluvium of directly neighbouring carbonate bedrock, and (2) sands eroded from the aeolian »basin«. Unit D also includes planar surfaces separating cross-stratified dune sands and overlaying Low-angle sands facies (Fig. 6, Log 3, 5.6 m and Log 4, 5.7 m), which probably originated by deflation. They seem to be preserved only locally, probably due to the destruction by subsequent streams. These surfaces might indicate hiatuses and represent super bounding surfaces.

The following segment of the studied succession provisionally designated as units E and F is known very fragmentary (Fig. 6) and future work is needed to show if the differentiation of units D, E and F could be based on more reliable data or altogether discarded. At present, the boundary between Units D and E has been tentatively placed at the height where cross-stratified sands are not observed anymore going up-section. Units E and F include Low-angle aeolian sands and Gravel-sand facies of fluvial origin (Fig. 27E). The boundary between Units E and F is partly based on tentative tephra-based correlation (Fig. 6).

The youngest part of the studied succession is represented by Cross-stratified sands of Unit G (Fig. 6) which is similar in character to Unit C discussed above. It reflects the onset of a period of intense, cold NE winds, high sand supply and intense sand accumulation, as well as a low water table – a situation similar to that related to Unit C. The base of Unit G probably represents a major stratigraphic surface, i.e. a super surface, as might also be the case of its top.

ASPECTS OF PALAEOGEOGRAPHY

Island of Mljet

The character of sand distribution, including its occurrence up to about 170 m (190 m?) a.s.l., suggests that sand was being deposited over a more extensive area compared to its present-day extent (Fig. 4). The sand transported by strong winds may have climbed rather steep, NNW slopes 150 m high, and have been laid down both on the slopes and over gently inclined surfaces and depressions located further downwind (Figs. 4 and 28). Preserved parts of the previously larger sand cover also occur at the shoreline, in well sheltered parts of bays: E part of Saplunara Bay and Blaca Bay (Fig. 4). At Blaca locality, there are also submerged aeolian sands close to the shoreline (Figs. 4 and 19). On less sheltered coasts, the sand was removed by the post-glacial transgression. Dominant NE, cold Pleistocene winds which once blew from Dinaric mountains, are similar to the present-day, strong, dry and cold Bora wind which also blows from the NE, mainly in winter (e.g. PENZAR *et al.*, 2001).

The modification of previous deposits observed in the lower part of the studied succession (Units A and B) presumably occurred during an interglacial period, probably the Last Interglacial Stage (discussed above) and related sea-level highstand(s), hence, at a time when the present-day island area was separated from the mainland.

The onset of the glacial period (probably Last Glacial) was accompanied by a relatively small drop in sea-level and caused an enlargement of the island surface while it still remained separated from the mainland. Such a situation corresponds to the initial aeolian deposition (Unit C) within the studied succession. Later, larger drops in sea-level during the glacial period may have caused the exposure of comparatively deeper parts of the sea bottom. However, only major sea-level drops could have been responsible for generating terrestrial island-to-mainland connections, and intermittent connection and disconnection intervals may be envisaged to have occurred during the glacial period in correspondence to the sea-level fluctuation. The most extensive emergence including an islands-mainland connection must have occurred when the sea-level fell to about 120 m below present sea-level, about 18000 yr BP (Late Glacial Maximum, CORREGGIARI *et al.*, 1996). Hence, the envisaged changes in palaeogeography only partly correspond to the ideas of a widespread, continuous emergence of SE Adriatic areas (now submerged) during the late Pleistocene (MILOJEVIĆ, 1927; MALEZ, 1971; MARKOVIĆ-MARJANOVIĆ, 1976, 1977; BOGNAR *et al.*, 1992).

The data on facies and the above discussion contribute to the identification of sand sources. Carbonate lithoclasts in the sands derived from the carbonate-dominated Dinaric mountains (typical of the Outer Dinarides), although a part of them may have been recycled from Palaeogene and Neogene clastics of the same areas. Lithoclasts of mafic and ultramafic rocks, as well as dominant orthopyroxenes, clinopyroxenes and amphiboles in heavy mineral associations indicate well known mafic, ultramafic and related sources in the Dinarides. A part of the sand constituents, mainly quartzite and quartz may have derived from Palaeogene flysch of the mainland (BOGNAR *et al.*, 1992). However, relevant Dinaric areas were not direct sources for the aeolian sands of Mljet Island. BOGNAR *et al.* (1992) proposed that the detritus was first transported by a river which deposited its load in the area located between Mljet Island and the mainland, and that winds then brought the sand to the island. The interpretation proposed here includes reworking of sands arriving to the coast by marine processes in shallow-marine to shoreline settings which caused the inclusion of marine, biogenic constituents into the sand. Due to the lowering of the sea-level this sand was exposed subaerially and became the dominant and presumably exclusive direct source of sand transported and deposited on Mljet Island by aeolian processes.

SE Adriatic archipelago

Aeolian sands on Hvar and Vis islands are regarded to have been supplied by N and NE winds during Pleistocene glacial periods (MARKOVIĆ-MARJANOVIĆ, 1976, 1977). The same wind type blowing from the NE, which was similar to the present-day Bora wind, is considered to have been deflected towards W and S directions when reaching Hvar Island due to the influence of local island topography (PAVELIĆ *et al.*, 2011). The data from Mljet Island described above indicates the same dominant winds.

The supply from exposed marine sands recorded in the studied succession of Mljet Island must have also occurred over a much wider area as it was related to the position of the sea-level. Hence, it is suggested that a major part of the aeolian sands on other islands of the SE Adriatic archipelago (Fig. 2) derived from exposed marine sands. The results of a reconnaissance study of these sands support this view (VIDOVIĆ *et al.*, 2012). This includes aeolian sands on Hvar Island (Fig. 2) which were presumed to have been sourced by alluvial sediments and dune fields located within alluvial plains (PAVELIĆ *et al.*, 2011).

SUMMARY AND CONCLUSION

The studied Pleistocene sands of Mljet Island include strongly modified sediments, aeolian deposits and fluvial deposits. Modified sediments originated from previously deposited sands and minor gravels which experienced a pedogenic homogenisation. Aeolian deposits are represented by deflationary gravel, dune cross-stratified sands and low-angle laminated sands. Most of the aeolian sands (if not all) were sourced from exposed, shallow-marine sands which were transported by strong NE winds. Fluvial deposits include gravels reworked from neighbouring carbonate slope, scree and colluvial deposits, and sands recycled from aeolian sands. Their deposition occurred by high-gradient streams which were flowing towards ENE to SE. There are at least two tephra horizons represented by clay. Shortly after the eruption and ash fall, the streams reworked the sand-grade volcaniclastic deposits together with aeolian sand which behaved hydrodynamically in the same way. Resultant beds may laterally contain different proportions of the two components: epiclastic tephra and recycled aeolian sand.

The lower part of the studied succession includes two major stratigraphic surfaces which are related to processes of landscape stabilisation and stratigraphic gaps, and correspond to super bounding surfaces. The third important stratigraphic surface of the studied succession occurs close to its top and may also be designated as a super surface.

Two modified units forming the lower part of the studied succession are relics produced during an interglacial (or interstadial) period. Subsequent aeolian sands reflect the onset of a glacial period with strong, cold winds, and a related initial sea-level fall resulting in the exposure of shallow-marine sands which became a source for aeolian deposits. It is tentatively proposed that the onset of aeolian deposition above the pedogenically modified sands corresponds to the onset of the Last Glacial period.

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REFERENCES

AHLBRANDT, T.S. & ANDREWS, S., 1978: Distinctive sedimentary features of cold-climate eolian deposits, North Park, Colorado. Palaeogeogr. Palaeoclimatol. Palaeoecol., 25, 327–351.

AHLBRANDT, T.S. & FRYBERGER, S.G., 1981: Sedimentary features and significance of interdune deposits. In: ETHERIDGE, F.G. & FLORES, R.M. (Eds.): Recent and Ancient Non-Marine Depositional Environments: Models for Exploration. SEPM Sp. Publ., Tulsa, 31, 293–314.

ANDREUCCI, S., CLEMMENSEN, L.B. & PASCUCCI, V., 2010: Transgressive dune formation along a cliffed coast at 75 ka in Sardinia, Western Mediterranean: a record of sea-level fall and increased windiness. Terra Nova, 22, 424–433.

BIGI, G., COSENTINO, D., PAROTTO, T., SARTORI, R. & SCANDONE, P., 1990: Structural Model of Italy, 1:500,000. Consilio Nazionale delle Riccerche. Roma.

BOGNAR, A., KLEIN, V., MESIĆ, I., CULIBERG, M., BOGUNOVIĆ, M., SARKOTIĆ-ŠLAT, M., HORVATINČIĆ. N., 1992: Quaternary sands at south-eastern part of the Mljet island. – In: BOGNAR, A. (Ed.): Int. Symp. Geomorphology and Sea, and Meeting of the Geomorphological Commision of the Carpatho-Balcan Countries Mali Lošinj, 1992, 99–110.

BROMLEY, R.G., 1996: Trace Fossils – Biology, Taphonomy and Applications. 2. Edition, Chapman & Hall, London, XVI+361 p.

CIMERMAN, F. & LANGER, M.R., 1991. Mediterranean Foraminifera. Classis IV: Historia Naturalis, Slovenska akademija znanosti in umetnosti. Ljubljana. Opera, 30, 1–118 p., 93 Plates.

CORREGGIARI, A, ROVERI, M. & TRINCARDI, F., 1996: Late Pleistocene and Holocene evolution of the north Adriatic sea. Il Quaternario, It. J. Quaternary Sci., 9/2, 697–704.

CREMASCHI, M., 1990a: Loess deposits in Northern and Central Italy. In: CREMASCHI, M. (Ed.): The Loess in Northern and Central Italy. Centro di Studio per la Stratigrafia e Petrografia delle Alpi Centrale. Editrice Gutenberg, Milan, 15–19.

CREMASCHI, M., 1990b: Stratigraphy and palaeoenvironmental significance of the loess deposits on Susak island (Dalmatian archipelago). Quaternary Int., 5, 97–106.

DORALE, J.A., ONAC, B.P., FORNÓS, J.J., GINÉS, J., GINÉS. A., TUCCIMEI, P. & PEATE, D.W., 2010: Sea-level highstand 81.000 years ago in Mallorca. Science, 327, 860–863.

DOTT, R.H. JR., BYERS, C.V., FIELDER, G.W., STENZEL, S.R. & WINFREE, K.E., 1986: Aeolian to marine transition in Cambro-Ordovician cratonic sheet sandstones of the northern Mississippi valley, USA. Sedimentology, 33/3, 345–367.

EKDALE, A.A., BROMLEY, R.G. & PEMBERTON, S.G., 1984: Ichnology – Trace Fossils in Sedimentology and Stratigraphy. SEPM Short Course, 15, Tulsa, 1–317 p.

FORNOS, J.J., CLEMMENSEN, L.B., GÓMEZ-PUJOL, L. & MURRAY, A.S.. 2009: Late Pleistocene carbonate aeolianites on Mallorca, Western Mediterranean: a luminescence chronology. Quaternary Sci. Rev., 28, 2697–2709.

FRYBERGER, S.G., AHLBRANDT, T.S. & ANDREWS, S., 1979: Origin, sedimentary features, and significance of eolian sand »sand sheet« deposits, Great Sand Dunes National Monument and vicinity, Colorado. J. Sedim. Petrol., 49/3, 733–746.

FRYBERGER, S.G., SCHENK, C.J. & KRYSTINIK, L.F., 1988: Stokes surfaces and the effects of near-surface groundwater-table on aeolian deposition. Sedimentology, 35/1, 21–41.

GRANDIĆ, S., BOROMISA-BALAŠ, E., ŠUŠTERČIĆ, M. & KOLBAH, S., 1999: Hydrocarbon possibilities in the Eastern Adriatic Slope zone of Croatian offshore area. Nafta, 50, 51–73.

GRUND, A., 1907: Die Entstehung und Geschichte des Adriatischen Meeres. Geogr. Jahresb. Österreich, 6, 1–14.

HAVHOLM, K.G. & KOCUREK, G., 1994: Factors controlling aeolian sequence stratigraphy: clues from super bounding surface features in the Middle Jurassic Page sandstone. Sedimentology, 41/5, 913–934.

HUNTER, R.E., 1977: Basic types of stratification in small eolian dunes. Sedimentology, 24/3, 361–387.

KOCUREK, G., 1981: Significance of interdune deposits and bounding surfaces in aeolian dune sands. Sedimentology, 28/6, 753–780.

KOCUREK, G. & NIELSON, J., 1986: Conditions favourable for the formation of warm-climate aeolian sand sheets. Sedimentology, 33/6, 795–816.

KOCUREK, G., KNIGHT, J. & HAVHOLM, K., 1991: Outcrop and semi-regional three-dimensional architecture and reconstruction of a portion of the eolian Page Sandstones (Jurassic). In: MIALL, A.D. & TYLER, N. (Eds.): The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery. SEPM Concepts in Sediment. Paleont., 3, 25–43.

KOCUREK, G. A., 1996: Desert aeolian systems. In: READING, H.G. (Ed.): Sedimentary Environments: Processes, Facies and Stratigraphy. 3. Ed., Blackwell Science, 125–153.

KORBAR, T. (2009): Orogenic evolution of the External Dinarides in the NE Adriatic region: a model constrained by tectonostratigraphy of Upper Cretaceous to Paleogene carbonates. Earth-Sci. Reviews, 96/4, 296–312.

KOROLIJA, B., BOROVIĆ, I., GRIMANI, I. & MARINČIĆ, S., 1976: KORČULA, Basic Geological Map of Jugoslavia, 1:100000. Inst. of Geol. Res. Zagreb, Federal Geol. Inst., Belgrade.

KOROLIJA, B., BOROVIĆ, I., GRIMANI, I., MARINČIĆ, S., JAGAČIĆ, T., MAGAŠ, N. & MILANOVIĆ, M., 1977: Explanatory notes for sheets LASTOVO, KORČULA, PALAGRUŽA. Basic Geological Map of Jugoslavia, 1:100000. Inst. Geol. Res. Zagreb; Federal Geol. Inst., Belgrade. 53 pp.

KRKALO, E. & PENCINGER, V., 1995: Mineralne sirovine otoka Mljeta. In: DURBEŠIĆ, P. & BANOVIĆ, A. (Eds.): Mljet, Prirodne značajke i društvena valorizacija otoka Mljeta. Zagreb, 147–154.

LANGFORD, R.P., 1989: Fluvial-aeolian interactions: Part I, modern systems. Sedimentology, 36/6, 1023–1035.

LANGFORD, R.P. & CHAN, M. A., 1989: Fluvial- aeolian interactions: Part II, ancient systems. Sedimentology, 36/6, 1037–1051.

LOEBLICH, A.R.Jr. & TAPPAN, H., 1987: Foraminiferal Genera and their Classification. Van Nostrand Reinhold, New York. 970 pp.

LUGOVIĆ, B., CRNJAKOVIĆ, M. & BIŠEVAC, V., 2006: Mineralogical signatures of weathered Late Holocene ash layer from the island of Mljet in Croatia. In: VLAHOVIĆ, I, TIBLJAŠ, D., DURN, G. & BIŠEVAC, V. (Eds.): 3rd Mid-European Clay Conference – MECC 06. Abstract Book. Prirodoslovno-matematički fakultet i Rudarsko-geološko-naftni fakultet, Zagreb, p. 78.

MALEZ, M., 1971: The colonization of Dinaric karst in Pleistocene – Naseljavanje Dinarskog krša u pleistocenu (In Croatian, Engl. summary). In: VARIĆAK, T. (Ed.): Simpozij o zaštiti prirode u našem kršu Jugosl. Akad. znan. umjet., Zagreb, 63–80.

MANGE, M. & MAURER, F., 1992: Heavy Minerals in Colour. Chapman & Hall, London. 147 pp.

MANVILLE, V., SEGSCHNEIDER, B & WHITE, J.D.L., 2002: Hydrodynamic behaviour of Taupo 1800a pumice: implications for the sedimentology of remobilized pyroclasts. Sedimentology, 49/5, 955–976.

MARKOVIĆ-MARJANOVIĆ, J., 1976: Sédiments Quaternaires dans l'Ile de Hvar – Adriatique Centrale (In Serb., French. Summary). Bull. Museum Hist. Natur., (A), 31, Belgrade, 199–214.

MARKOVIĆ-MARJANOVIĆ, J., 1977: Quaternaire dans l'Ile de Vis (In Serb., French. Summary). Bull. Museum Hist. Natur., (A), 32, Belgrade, 145–161.

MIALL, A.D., 1996: The Geology of Fluvial Deposits. Springer, Berlin. 682 pp.

MIKULČIĆ PAVLAKOVIĆ, S., CRNJAKOVIĆ, M., TIBLJAŠ, D., ŠOUFEK, M., WACHA, L., FRECHEN, M. & LACKOVIĆ, D., 2011: Mineralogical and geochemical characteristics of Quaternary sediments from the Island of Susak (Northern Adriatic, Croatia). Quaternary Int., 234/1–2, 32–49.

MILOJEVIĆ, B.Ž., 1927: Ostrvo Vis. Glasnik Zemaljskog muzeja Bosne i Hercgovine, 39/1, 111–124, Sarajevo.

MOUNTNEY, N.P., 2006a: Periodic accumulation and destruction of aeolian erg sequences in the Permian Cedar Mesa Sandstone, White Canyon, southern Utah, USA. Sedimentology, 53/4, 789–823

MOUNTNEY, N.P. 2006b: Eolian facies models. In: POSAMENTIER, H.W. & WALKER, R.G. (Eds.): Facies Models Revisited. SEPM Spec. Publ. 84, 19–83.

MOUNTNEY, N.P. & THOMPSON, D.B., 2002: Stratigraphic evolution and preservation of aeolian dune and damp/wet interdune strata: an example from the Triassic Helbsy Sandstone Formation, Cheshire Basin, UK. Sedimentology, 49/4, 805–833.

MURRAY, J.W., 2006: Ecology and Applications of Benthic Foraminifera. Cambridge University Press, Cambridge. 426 pp.

PAVELIĆ, D., KOVAČIĆ, M., VLAHOVIĆ, I. & WACHA, L., 2011: Pleistocene calcareous aeolian-alluvial deposition in a steep relief karstic coastal belt (island of Hvar, eastern Adriatic, Croatia). Sediment. Geol., 239/1–2, 64–79.

PENZAR, B., PENZAR, I. & ORLIĆ, M., 2001: Vrijeme i klima Hrvatskog Jadrana. Nakladna kuća Dr Feletar, Zagreb, 258 pp.

PIGORINI, B.. 1968: Sources and dispersion of recent sediments of the Adriatic Sea. Marine Geology, 6/3, 187–229.

POSTMA, G., 1983: Water escape structures in the context of a depositional model of a mass flow dominated conglomeratic fan-delta (Abrioja Formation, Pliocene, Almeria Basin, SE Spain). Sedimentology, 30/1, 91–103.

RAJIĆ, V., PAPEŠ, J., AHAC, A., KOROLIJA, B., BOROVIĆ, I., GRIMANI, I. & MARINČIĆ, S., 1982: STON, Basic Geological Map of Jugoslavia, 1:100000. Geoinženjering-Inst. Geol. Sarajevo, Inst. of Geol. Res. Zagreb, Federal Geol. Inst., Belgrade.

RODRIGUEZ-LÓPEZ, J.P., MELÉNDEZ, N., DE BOER, P.L. & SORIA, A.R., 2010: The action of wind and water in a mid-Cretaceous subtropical erg-margin system close to the Variscan Iberian Massif, Spain. Sedimentology, 57/5, 1315–1356.

STOKES, W.L., 1968: Multiple parallel truncation bedding planes – a feature of wind deposited sand formations. J. Sedim. Petrol., 38, 510–515.

TALBOT, M.R., 1985: Major bounding surfaces in aeolian sandstones-a climatic model. Sedimentology, 32/2, 257–265.

VEIGA, G.D., SPALLETTI, L.A. & FLINT, S., 2002: Aeolian/fluvial interactions and high-resolution sequence stratigraphy of a non-marine lowstand wedge: the Avilé Member of the Agrio Formation (Lower Cretaceous), central Neuquen Basin, Argentina. Sedimentology, 49/5, 1001–1019.

VIDOVIC, J., BABIC, L., ZUPANIC, J., RAZUM, I. & CRNJAKOVIC, M., 2012: Foraminifera-bearing aeolianites of SE Adriatic islands, Croatia. 29. IAS Meeting of Sedimentology, Sedimentology in the Heart of the Alps, Programme, p. 181.

VLAHOVIĆ, I., TIŠLJAR, J., VELIĆ, I. & MATIČEC, D., 2005: Evolution of the Adriatic Carbonate Platform: Palaeogeography, main events and depositional dynamics. Palaeogeogr. Palaeoclimatol. Palaeoecol., 220, 333–360.

WACHA, L., MIKULČIĆ PAVLAKOVIĆ, S., NOVOTHNY, Á., CRNJAKOVIĆ, M., FRECHEN, M., 2011: Luminescence dating of Upper Pleistocene loess from the Island of Susak in Croatia. Quaternary Int., 234/1–2, 50–61.

WALKER, T.R., 1967: Formation of red beds in modern and ancient deserts. Geol. Soc. America Bull., 78/3, 353–368.