Records of Climate Change over the Late-Holocene in the Danube Delta Coastal Dune System

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Key words: aeolian activity, Danube delta, parabolic dunes, Optical Stimulated Luminescence (OSL), dendrochronology

Abstract: The largest dunefields in the Danube delta developed during the Late-Holocene on the Caraorman and Letea prograded barriers. The sand dunes in the Danube delta are one of the most pristine coastal dunes in Europe. Our research focused upon the reconstruction of aeolian landforms in the Danube delta.

Field based investigations of the modern aeolian morphology revealed the succession of different aeolian activity phases shaping the modern aeolian landforms. One phase of aeolian modification of the landforms occurred during conditions of generally low rugosity (bare and grassy areas) while another one followed when the development of aeolian landforms was constrained by the emplacement of woody vegetation. The highest altitudes of the prograded barrier at Letea correspond to the accretion fronts developed in association with the forest.

Mapping of the morphologic features of the Letea complex ridge plain shows the discordant superposition of the aeolian landforms over the marine wave-laid sediments (beach ridges). The relationship between the resultant migration direction of the dunes (RMDD) and the underlying beach ridge orientation is an important controlling factor on the development of the aeolian morphology. Elongated parabolic dunes occur where the RMDD is concordant with the subjacent beach ridge alignment.

A combination of dendrochronological dates and optically stimulated luminescence (OSL) ages were used in order to develop a chronology of aeolian activity in the Danube delta during the Late-Holocene. The preliminary OSL ages indicate that the interplay between sea-level, sediment availability and climate variability over the last 2400 yrs resulted in a dunefield pattern representing several dune generations.

Our OSL ages, together with the ages produced by Giosan et al. (2006) advocate for a new hypothesis regarding Letea complex ridge plain development according to which at least three phases with different rates of progradation occurred: (1) rapid rates at the beginning, since 3640 ± 460 yr B.P. to 2300 ± 480 yr B.P., (2) slow rates since 2300 ± 480 yr B.P to 900-1200 yr B.P. and (3) rapid rates since 900-1200 yr B.P.until the initiation of the Chilia secondary delta.

Introduction

The open coast Danube delta started to develop 5210±280 yrs. B.P. (Giosan et al., 2006), leading to the development of a 30 km wide deltaic plain. Delta progradation occurred at different rates resulting in distinct morphological settings. One of the most significant morphological characteristics of the Danube delta is represented by the extensive dunefields from Letea and Caraorman prograded barriers. These dunes represent the largest aeolian landforms (aeolian sand volumes) from the Black Sea basin. They stand for one of the most pristine coastal dunes in Europe. Despite their potential role in the Danube delta development and their capacity to deliver information about the paleoenvironmental changes, these dunes, like all the coastal dunes from the Black Sea basin, remain little studied, representing thus a missing piece of the general picture of Holocene aeolian activity in Europe.

This is the first study aiming to determine the emplacement time of dune fields from the Danube delta and to give a first description of their internal structure, morphology and development pattern. The dunefields developed on the Letea and Caraorman prograded barrier represent geomorphic features that encompass high resolution records of coastal and eolian processes involved in their development. Our data together with those produced elsewhere across Europe (Clemmensen et al., 1996, Clemmensen et al., 2001, Orford et al., 2000, Wilson et al., 2001, Wilson, P., 2002, Clarke et al., 2002, Clarke and Rendell, 2006, Buynevich et al., 2007, Clemmensen et al., 2007) contribute to the building of a general picture of Late Holocene aeolian activity in Europe. Understanding the effects of environmental and anthropogenic changes on coastal landscapes is particularly important in a current regime of rapid shifts in climate, sea level, and sediment supply, combined with ever increasing population pressures along sandy coasts (Buynevich et al., 2007). Furthermore, this information could be used for predicting the possible effects which changes in sea level and wind/wave climate may have on coastal environments during the next century (Pye and Neal, 1993).

A combination of optically stimulated luminescence (OSL) ages, dendrochronological dates as well as field based morphological investigation and maps interpretation were used in order to develop a preliminary chronology of the late Holocene aeolian activity in the Danube delta.

Methodology

Two fieldwork campaigns were undertaken in autumn 2006 and spring 2007 when geomorphological observations and sand samplings for OSL dating were carried out on the Letea and Caraorman prograded barriers. Topographic measurement were performed in order to obtain the Digital Elevation Model (DEM) of morphodinamically representative parabolic dunes using a Sokkia 610 total station.

Dune age was determined using optical stimulated luminescence (OSL). Optical dating is used to determine the period of time elapsed since the mineral grains were last exposed to daylight. Aeolian sands are ideal materials for the application of OSL dating technique because quartz grains are usually well exposed to light during aeolian transport (Wintle, 1993). The time since last exposure to the daylight is calculated by dividing the apparent dose (Gy) absorbed from naturally occurring ionizing radiation by the dose rate (Gy/ka). In our study, clean sand size grains of quartz were obtained after sieving and chemical treatment (10% HCl for carbonate removal, H_2O_2 for organic fraction removal). The 180-212 µm quartz fraction was separated of heavy minerals and feldspars using Sodium Politungstate (with a density 2.7 g/cm^3, respectively 2.62 g/cm^3). The new obtained quartz fraction was then treated with HFl for the external layer removal, than re-sieved. The 150-180 µm was then used for aliquots preparation under subdued orange lighting. The radiation measurement was performed with a TL/OSL Risø reader equipped with an EMI 9635QA photomultiplier and 2 Hoya U-340, 3 mm thick filters. Single Aliquot Regeneration (SAR) dose protocol (Duller, 2004) was used to estimate the radiation dose that the samples had absorbed during burial. This protocol makes repeated OSL measurements of each sub-sample, or aliquot, so that the growth of the luminescence signal as a function of laboratory radiation dose can be determined. The importance of SAR procedure resides in OSL signal sensitivity changes assessment and addressing this issue.

Within the SAR sequence, all OSL measurements were made while holding the sample at 125°C. The natural and regeneration signals were measured following a preheat step of 220°C for 10 seconds, and the test dose following heating to 160°C. To test the appropriateness of this SAR protocol to these samples, between 2 and 6 aliquots of each sample were bleached in the laboratory (using two sets of 100s exposures to blue diodes) and then given a known laboratory radiation dose. Additionally, 20 aliquots of Letea 5 were exposed to the sunlight and then the dose recovery test was performed. The ratio of the given laboratory dose to that which was measured varied from 0.96 to 1.03, demonstrating that SAR is appropriate for these samples.

In order to build a long dendrochronological series living old oak trees were chosen in accordance with dendrochronological principles (Fritts, 1976; Cook and Kairiukstis 1990; Popa 2004a). Because of protective status of forest only one core have been extracted from each tree with an increment borer at breast height. All samples were dried out and sanded to improve the visibility of tree-ring borders. The LINTAB equipment and TSAP software were used for measuring the annual ring-widths with a precision of 0.01 mm, as well as for cross-dating the growth series by graphical comparison (Rinntech, 2005). The results were checked for missing ring and dating error using the COFECHA software through the analysis of the correlation on intercalated subperiods (Holmes, 1983; Grissino-Mayer, 1997). The final dataset comprises 55 individual series (25 from Caraorman and 30 series from Letea). The growth series were standardized in order to eliminate the non-climatic trend and to maximize the climatic information from the individual series. A double standardization was applied: first a rigid cubic spline with a 50% frequency response cutoff width equal to 200 years to remove the age effect and a second, more flexible, cubic spline of 10 years to preserve only the high frequencies signal.

All detrended series were averaged to chronology using biweight robust mean (Cook, 1985).

Regional settings

Letea and Caraorman dunefields developed in the central part of the Danube delta, at about 25 km landward (Westward) from the modern shoreline. The Danube delta dunefields currently evolve under a temperate dry climate, with average precipitation amount of about 300-350 mm/year which renders it the driest region in Romania with 104 days of drought and 200.3 dry days at Sulina (Barbu and Popa, 2002). A recent study undertaken by Bălteanu et al. (2008) reveals a tendency toward a drier climate with a decrease of the mean annual precipitation recorded at the meteorological stations from the Danube delta during the last four decades: -2.4 mm/yr at Sulina, -3.1 mm/yr at Gorgova and -3.7 mm/yr at Sfântu Gheorghe. The mean multiannual temperature is 11˚C with sharp differences between the seasons (January: -0.2 ^{0}C; August: 21.8 ^{0}C). The wind climate is macroenergetic (63.03 vu according to Fryberger technique, 1978) and the prevailing winds are from north and display an accute bimodal distribution: NW-NE (Preoteasa and Vespremeanu-Stroe, 2004). As a consequence, the aeolian morphology is mainly represented by parabolic dunes, elongated parabolic dunes and nebckha dunes.

Danube delta developed under the alternating control of fluvial and marine factors. Since the beginning of delta development, Danube sediment discharge fluctuated in relation with the climate variability (Giosan et al., 2006), but generally recorded the same order of values as in the period before damming: 6.8 x 10^{10} kg/yr (Almazov et al., 1963). Black Sea is a tideless basin and the significant wave height measures 0.9m (Vespremeanu-Stroe, 2004). The modern longshore sediment drift values were assessed through sedimentary budget method - computations of reworked sediment volumes (0.7 x 10^6 m^3/yr - Panin, 1972, 1984) and by modeling the nearshore wave transformation (0.85 x 10^6 m^3/yr - Giosan et al., 1999; 1 x 10^6 m^3/yr – Vespremeanu-Stroe, 2004).

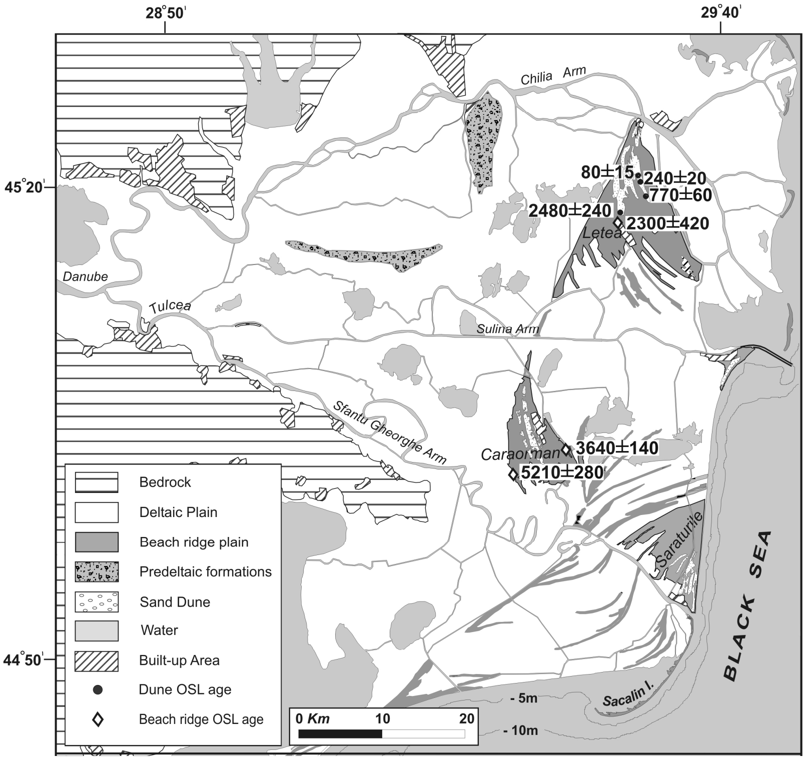

Fig. 1. **Danube Delta map and location of OSL samples**
(OSL ages are expressed as years before AD 2006; the beach ridge ages on Caraorman are cited from Giosan et al., 2006 and are expressed as years before AD 2004) (after Preoteasa et al., 2009)

According to the most recent studies (Giosan et al., 2006), the Caraorman prograded barrier started (Fig. 1) to form 5600 years ago in association with the Sfântu Gheorghe (Southern branch of the Danube) arm mouth. Since then, the barrier evolved through deposition of the sediment transported by the longshore currents updrift of the arm mouth. This pattern of progradation was interrupted when the Sulina arm (the central branch of the Danube) discharge rose and the arm mouth pervaded seaward, delivering Danubian sediments for downdrift deposition. The transition moment from marine to danubian sediment deposition was dated 3640 yrs. B.P. (Giosan et al., 2006). This is also considered the moment when the Letea prograding barrier (Fig. 1) started to form by sediment accumulation updrift of Sulina arm mouth. The preliminary geochronological results yielded from this study confirm this hypothesis.

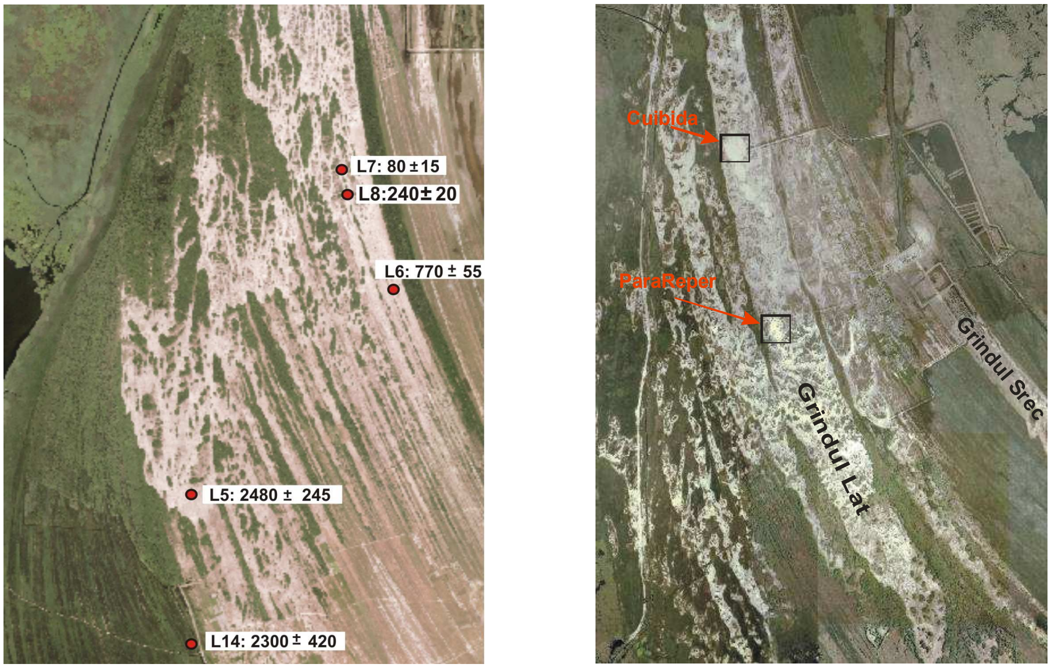

Fig. 2. – a) **Ortophotograms (2005) showing the sand dunes on the Letea prograded barrier and OSL ages location** (the ages are expressed as years before 2006) and b) **the sand dunes from the Caraorman prograded barrier** (2006)

A sand sample taken from marine sediments of the beach ridge situated at about 2 km seaward (E) from the Western edge of the Letea prograded barrier, over which the first aeolian deposits overlay, was dated 2300 ± 420 yr B.P. The progradation occurred at different rates, resulting in distinct morphologic patterns: the rapid progradation rates resulted in beach ridge morphology while the slower progradation rate enabled dune ridges building. The mineralogical analysis shows that the aeolian landforms primarily consist in allochtonous clastic sediments originating from the Northern part of the Black Sea Basin, transported by the longhshore currents (Panin, 1989; Giosan et al., 2006). Quartz minerals prevail within the marine sand while mica is characteristic for Danubian discharged sediment. The mean grain size of the marine sand varies between 0.22-0.26 mm while the danubian sand is generally finer (< 0.20 mm) (Preoteasa, 2008).

Morphology and chronology of the sand dunes from Letea and Caraorman prograded barriers

Although the two dunefields are only 20 km apart (on an N-S orientated axis) (Fig. 1), they display different patterns of spatial organization of the aeolian features (Fig. 2a,b).

On the Caraorman prograded barrier, aeolian landforms are concentrated within parallel elongated strips, N-SSE oriented, which generally follow the alignment of the underlying marine ridges and of primary foredunes. The dunes are concentrated mostly in the central part.

Commonly the aeolian landforms are represented by dune complexes or individual dunes. Dune complexes regularly consist of parabolic dunes, blowouts and remnant knobs. Most of these evolve under a negative sand budget as no external sediment source to the Caraorman barrier is available, but the reworking of the existent sand. The aeolian features are superimposed on parallel or sub-parallel ridges, which represent ancient shorelines and which are generally N-SSE orientated. The preexisting topography of these ancient shorelines influenced the pattern of spatial organization of the aeolian landforms as parallel alignments on the Caraorman complex ridge plain. The dunes are northward orientated, with small disturbances induced by wind deflection and channeling effects generated by the existent topography. The observations and measurements we performed on five representative dune complexes reveal a concordance between the steepest slope orientation and the prevalent winds. Thus the extensively existing steepest slopes are NNV exposed, while the resultant drifts direction is 178,1 ^{0}.

On the Letea prograded barrier, the aeolian features are concentrated within three large (between 5-10 km^2 each) parabolic-shaped complexes which are situated on the NW part of the barrier, generally N-S orientated (Fig. 2a). The relationship between aeolian landforms orientation and that of the underlying beach ridges is discordant within the southernmost complex and concordant within the central and the northern complexes. Field based observations of the modern morphology revealed the presence of inactive parabolic dunes and nebkhas within the southernmost complex, while the central and northernmost complex display a wide range of overlapping sets of parabolic dunes, nebkhas, blowouts varying from individual parabolic dunes to compounded (nested) parabolic dunes and elongated parabolic dunes. Within the northernmost dunefield the elongated dunes prevail. Previous studies related the formation of elongated dunes with the prevalence of high wind speeds (Gaylord and Downson, 1987; Pye, 1983). Our observations revealed the occurrence of such landforms at locations where the resultant drift direction is concordant with the orientation of the subjacent topography. The morphology and morphodynamics of each dune complex is probably related to variations of aeolian activity and sediment availability. In contrast, dunes didn't form in the eastern part of the Letea and Caraorman prograded barriers, where numerous beach ridges rapidly formed out of fluvial sediments.

Field based investigations of the modern aeolian morphology revealed the succession of different aeolian activity phases in shaping the modern aeolian landforms. One phase of aeolian modelling of the landforms (Fig. 3) occured during general low rugosity conditions (bare and grassy areas) and a second one when the aeolian landforms development was constrained by the presence of woody vegetation (*Querqus sp.*) (Fig. 4). Field evidences account for two generations of forest. The oldest trees, were found within the swale areas (Fig. 4). The younger forest generation, whose age was determined as 280 yrs., developed within the interdune areas and blowouts. The highest altitudes of the Letea prograded barrier corresponds to the accretion fronts developed in association with the forest (Fig. 4) (Preoteasa et al., 2009).

Interpretation of the ortorectified aerial photographs of the Letea prograded barrier revealed the discordant superposition of the aeolian landforms over the marine wave-laid sediments as beach ridges. The high discrepancy between the aeolian features orientation and the beach ridges over which they transgress on the southwestern part of the dunefield may account for a long period of aeolian sediment remobilisation. The relation between the resultant migration direction of the dunes (RMDD) and the underneath beach ridge orientation is an important controlling factor of the aeolian morphology development. Elongated parabolic dunes occur where the RMDD is concordant with the subjacent beach ridge alignment.

Fig. 3. **Aeolian features developed during low ruguosity conditions** (bare surface)

Fig. 4. **Aeolian accretion front developed in association with the forest**

Table 1. **Equivalent dose** (D_e), dose-rates, and optically stimulated luminescence (OSL) **ages of sand dunes** (samples Aber111/L5-L8) **and beach ridges** (sample Aber111/L14) **from the Letea prograded barrier** (after Preoteasa et al., 2009)

Sample No.	Depth (cm)	Height above aeolian/ marine contact (cm)	Water content (%)[†]	D_e (Gy)[*]	n[‡]	External β dose-rate[‖]	External γ dose-rate[‖]	Cosmic dose-rate[§]	Total dose-rate[‖] (Gy/10^3 yr)	Age (yr)[¶]
L5	110	30	20 ± 5	1.29 ± 0.12	20	0.216	0.126	0.177	0.52 ± 0.02	2480 ± 240
L6	120	30	20 ± 5	0.50 ± 0.03	24	0.315	0.165	0.177	0.66 ± 0.02	770 ± 60
L7	160	400	5 ± 3	0.05 ± 0.01	20	0.255	0.145	0.170	0.57 ± 0.02	80 ± 15
L8	160	450	5 ± 3	0.13 ± 0.01	24	0.242	0.134	0.170	0.55 ± 0.02	240 ± 20
L14	100	-	20 ± 5	2.01 ± 0.36	22	0.451	0.246	0.176	0.87 ± 0.03	2300 ± 420

[†]. Water content expressed as a percentage of the mass of dry sediment, calculated based on measured field values.

[*]. The D_e shown is calculated as the weighted mean and standard deviation.

[‡]. 'n' is the number of D_e determinations.

[‖]. Dose-rate values (Gy/10^3 yr) were calculated using the conversion factors of ADAMIEC and AITKEN (1998) and are shown rounded to 3 decimal places, although the total dose-rates and ages were calculated using values prior to rounding. Central values are given for dose-rates – errors are incorporated into that given for the total dose-rate.

[§]. The cosmic ray dose-rate (Gy/10^3 yr) was estimated for each sample as a function of depth, altitude, and geomagnetic latitude (PRESCOTT and HUTTON, 1994).

[¶]. Luminescence ages are expressed as years before 2006 AD, and rounded to the nearest 10 years for ages >100 years, and to the nearest 5 years for ages < 100 years.

Our ages (Table 1), together with the ages produced by Giosan et al. (2006) advocate for a new hypothesis regarding the Letea prograded barrier development according to which at least three phases with different rates of progradation occured: (1) rapid rates at the beginning: since 3640 ± 140 yr B.P (Giosan et al., 2006) to 2300 ± 480 yr B.P., (2) slow rates since 2300 ± 480 to 900-1200 yr B.P (uncertain radiocarbon age: Giosan et al., 2006), (3) rapid rates since 900-1200 yr. B.P. until the initiation of the Chilia secondary delta (Fig. 1). The different rates of progradation resulted in distinct morphological features: *beach ridges*, 6 km wide, developed as a result of high prograding rates and *foredune ridges,* emplaced during the slow prograding phase. The different widths of foredune ridges area in the northern (cca. 1 km), central (cca. 2 km) and southern (4 km) parts suggest different mean progradation rates varying from less than 1m/yr on the northern part to 2-3 m/yr on the southern part.

The concentration of the largest aeolian sand volumes on the N, NW part of the barrier could be interpreted as the alongshore variation of the foredune volume in relation with the LST (which is the main sediment source for Caraorman and Letea dunes). This alongshore foredune volume variability hypothesis is sustained by the reiteration of the same pattern over the entire width of the barrier (occupied with dunes) which developed within a time interval of 1600-1800 years. Their localization in the N, NW part of the barrier could have been promoted by the position in relation with the alongshore currents sediment transport capacity and shoreline exposure to the prevalent winds and waves. Subsequently, the rugged aeolian morphology concentrated on the northern part of the barrier was easily reworked by the prevalent northern winds and redistributed southward (downdrift) to finally form just a thin veneer of aeolian sand overlying the beach ridges.

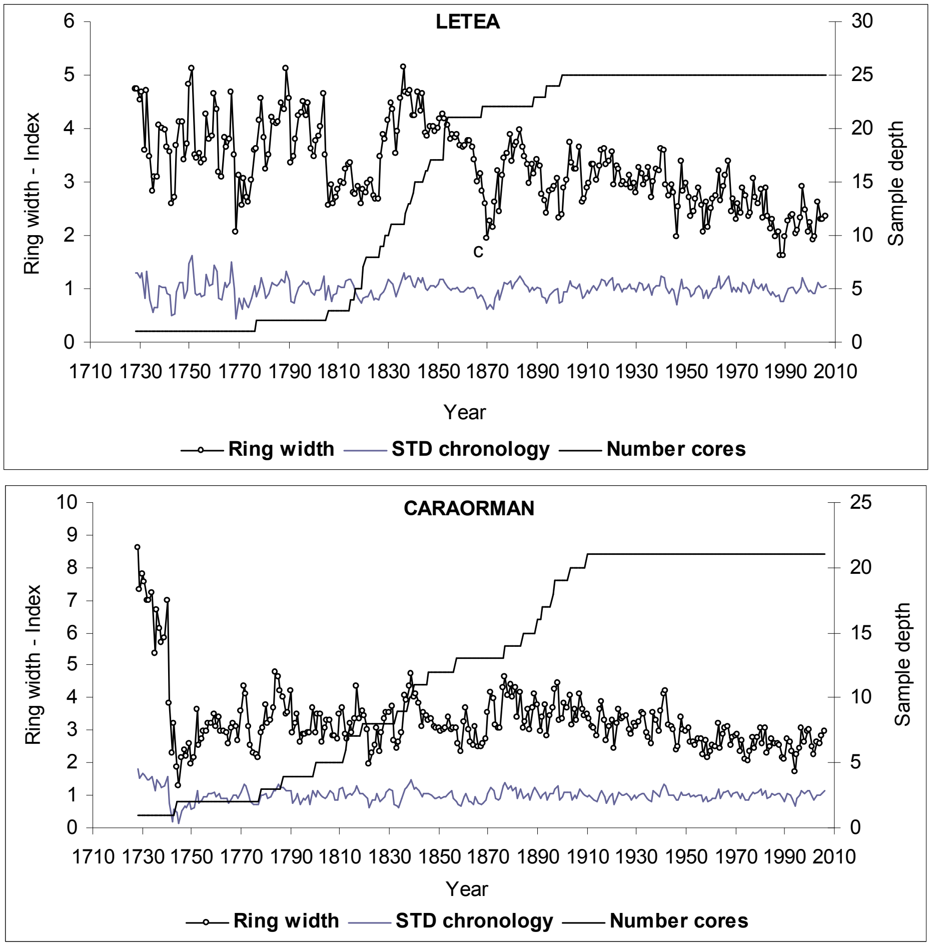

Fig. 5. **Dendrochronological analysis of Letea and Caraorman forest**

The stable behaviour of the shoreline on the northern sector permitted an important sedimentary transfer from nearshore to beach-dune system enabling thus the development of the large foredunes. The altitude of beach ridges is almost similar over the entire prograded barrier suggesting the fact that a steady wave climate and small sea level changes occured during the Upper Holocene (Giosan et al., 2006).

The integrated geochronologic and morphometric analysis of some representative sand dunes from the Letea and Caraorman prograded barriers revealed a high rate of sand transport averaging 0.68 m/yr within the last 240 yrs.

The tree ring growth analysis presents more time intervals when the tree development was unusualy slow (Fig. 5). Some of these intervals are correlated to drought intervals as suggested by tree ring growth characteristics and as recorded by hydrographical and meteorological measurement (e.g. 1870, 1946-1947), while some others do not correspond to drought records. The slow tree ring growth intervals that the dendrochronological analysis highlights are: 1767-1776 (Letea) and 1770-1778 (Caraorman); 1802-1828 (Letea) and 1806-1814/ 1820-1828 (Caraorman) and 1982-1995 (Letea) and 1982-1995 (Caraorman) (Fig. 6). Significant are the duration of these intervals (9-20 years) and the synchronous biological processes that occur within the forests on the two prograded barriers.

Letea 8 age fits well within the interval of slow three development recorded between 1767-1776 suggesting the high sand transport rates as a potential explanation.

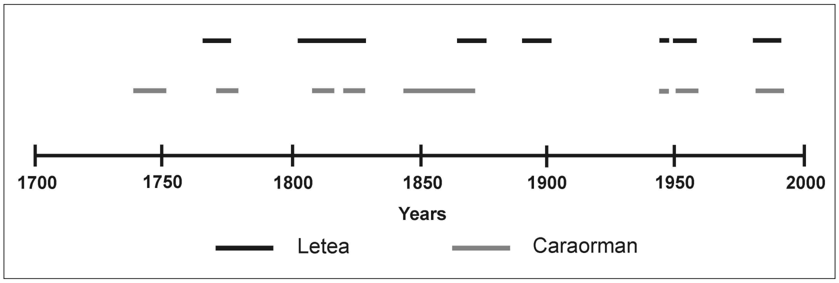

Fig. 6. **Slow tree ring development time intervals in Letea and Caraorman forests**

Conclusions

Preliminary OSL ages of Letea dune field indicate their formation during several episodes. They formed as successive seaward advancing foredune ridges between 2400 yrs and 770 yrs ago. The first aeolian landforms were synchronous with the process of eastward barrier progradation. Their evolution involved a primary phase when they developed as a result of the sedimentary exchange within the beach – dune system resulting into parallel foredune ridges. The constant barrier progradation lead to sedimentary flux decoupling between foredune ridges and the adjacent beach. A second phase followed consisting in several episodes of aeolian reworking of sediments already existing into the system. The interplay between the sedimentary flux and the woody vegetation resulted into the modern configuration of the aeolian landforms on which several episodes of aeolian activity could be detected. The most recent aeolian activity episodes occurred 240-70 yrs ago possibly controlled by the climatic variability during the Little Ice Age. The tree ring growth analysis presents more time intervals when the tree development was unusualy slow. Some of these intervals are correlated to drought intervals as suggested by tree ring growth characteristics and as recorded by hydrographical and meteorological measurements (e.g. 1870, 1946-1947), while some others do not correspond to drought records. Letea 8 age fits well within the interval of slow tree development recorded between 1767-1776 suggesting the high sand transport rates as a potential explanation.

The correlation between NAO index, precipitations and tree ring development revealed slow tree ring growth during the positive phases and rapid development during the negative phases.

The marine origin of the dune substrate justifies a regressive (prograding) barrier development model. Other papers dealing with aeolian landscape reconstruction elsewhere in Europe, report intensive episodes of aeolian activity within the last 250 yrs. For example, Clarke and Rendell (2006) documented a recent dune building episode in Portugal, occuring between 1770-1905 AD, Murray and Clemmensen (2001) identified the most recent aeolian activity phase at Thy, Denmark, starting earlier than 200 yrs ago, and Clemmensen et al. (2007) established the chronology of the last aeolian activity phase between 1640 and 1900 AD.

Acknowledgements:

The research activities were funded from CNCSIS research grant no 2916/200 awarded to Luminiţa Preoteasa. The authors would like to thank Florin Tătui, Florin Filip, Andrei Ghib and Mihaela Fâstac for their assistance during the fieldwork campaigns. Dr. Ştefan Constantinescu is acknowledged for supplying us helpful maps and aerial photos. Special thanks are due to Dr. Liviu Giosan for his helpful ideological and scientific support.

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