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Morphodynamics of intertidal sand bars: field studies in the Northern Adriatic, NE Italy.

Y. Balouin†, P. Ciavola†, G. Anfuso‡, C. Armaroli†, C. Corbau†, and U. Tessari†

†Dip. Scienze della Terra, Universita di Ferrara, Via Saragat 1, 44100 Ferrara, Italia
Email: y.balouin@brgm.fr

‡ Dep. Ciencias de la Terra, Faculdad de Ciencias del Mar y Ambientales, Universidad de Cádiz, 11510 Puerto Real, Cádiz, España

ABSTRACT

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Swash bars onshore migration have been measured on intertidal area of two microtidal beaches of Northern Adriatic during very low wave energy conditions. Bed microtopography was performed at every low tides, and migration of features followed by rods in a cross-shore array. Very small swash bars (A<0.07m, 2<L<10 m) were identified all over the intertidal zone, and their formation was always associated with a slack water tidal level. Despite the virtual absence of waves (Hs of 0.04-0.08 m at the Volano site), a important landward migration was measured (0.5-3 m/day). This migration is associated with an onshore sediment transport. The very low wave energy permits to assess the action of swash processes alone on the bar morphodynamics. A direct relationship was found between the bar migration rate and the duration of swash action over the bar crests. A similar study was performed on a bigger intertidal bar at Lido di Dante, while it was exposed to swash processes. Despite differences in bar nature and evolution, the landward bar migration also showed a strong relationship with the duration of swash action, excepted when longshore currents were evidenced, decreasing the deposition on the slip landward face, and thus the migration rate.

ADITIONAL INDEX WORDS: *swash processes, onshore bar migration.*

INTRODUCTION

Sandbar systems are features found along many coasts in a wide range of environments and they can occur in a variety of forms, sizes and numbers (KING and WILLIAMS, 1949; GREENWOOD and DAVIDSON-ARNOTT, 1979; AAGAARD and MASSELINK, 1999; DAWSON et al., 2002; WINJBERG and KROON, 2002).

Swash bars correspond to the group II of the bar classification of GREENWOOD and DAVIDSON-ARNOTT (1979). They have been observed on micro-meso-tidal beaches where slopes are moderate to steep (DAVIS et al., 1972; OWENS and FROBEL, 1977; DABRIO and POLO, 1981; KROON, 1998; DEGRYSE et al., 2001; STEPANIAN, 2002) and lakes (DAVIDSON-ARNOTT, 1988). They usually have small amplitude (<1 m) and wavelengths that range from 10 to 70 m. They are generally found near the low tide level, but can also appear close to the high tide level (STEPANIAN, 2002), where they have a small height and are generally formed under low energy wave conditions. If the wave energy remains low after the formation of the bars, they can either remain stable or migrate onshore. This migration is thought to be related to the onshore displacement of the swash and surf zones during the flood tide, especially when the tidal range increases from neap to spring tide (KROON, 1994). At high tide level, the swash is with no doubts the main control process, while surf bores are described as the main physical agent on the intertidal area (KROON and MASSELINK, 2002). Moreover, during most field studies, complexity and interactions between morphology, wind waves and infragravity waves, seepage and tidal levels have been observed (STEPANIAN, 2002), and the identification of a key process is often impossible.

In the present study, swash bars have been observed all over the intertidal area of microtidal beaches during a very low wave climate (Figure 1). Waves were transformed directly into swash on the beachface. These calm and simple conditions offered the opportunity to identify the processes responsible for swash bars morphodynamics.

Physical settings of the studied areas

Tidal regime in Northern Adriatic is strongly asymmetric, showing both diurnal and semi-diurnal components (see Figure 2). Maximum tidal range is about 1.2 m during spring tides. The wave climate is usually low energy with significant wave heights less than 0.5m, mainly from East (more than 65% of occurrences, GAMBOLATI et al., 1998). Two different storms prevail in the Adriatic Sea: the Scirocco from SE, and the Bora from NE.

Field studies were undertaken on two different beaches: i) the site of Lido di Volano, characterized by a single bar-trough system where secondary swash bars are observed all over the intertidal area (Figure 1); ii) Lido di Dante where intertidal bars usually show a rhythmic pattern associated with subtidal crescentic bars. The beach gradient is low (mean slope ranges from 2 to 4%) and the sediment is composed of fine to medium sands (D_{50}~200 µm).

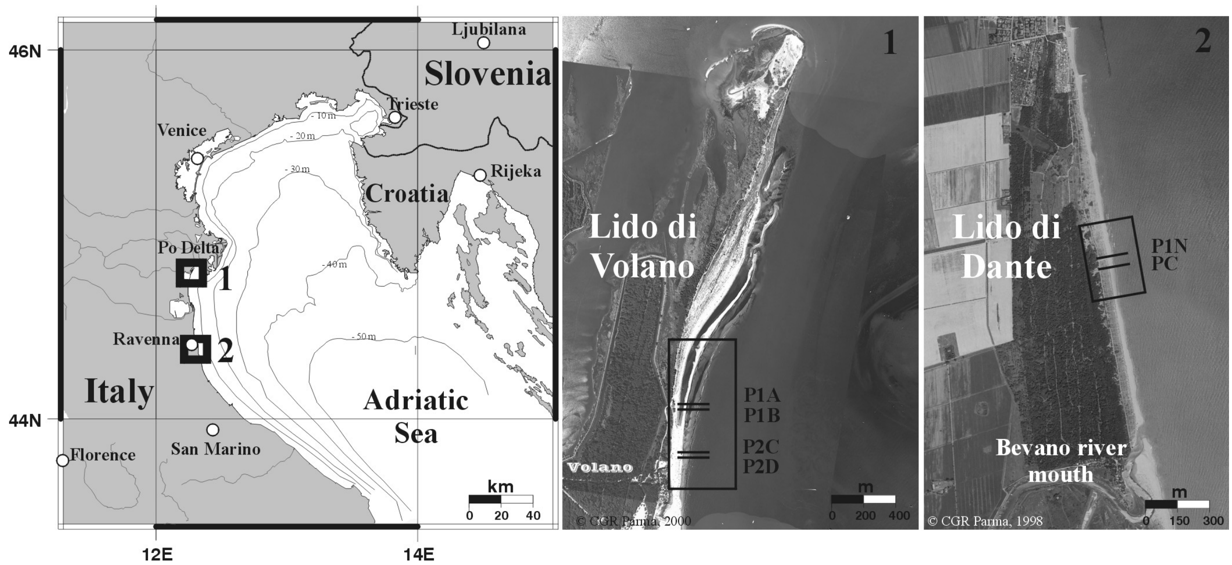

Figure 1: Field sites in Northern Adriatic Sea.

METHODS

Fieldwork was undertaken in January 2003 at Lido di Volano and in April 2003 at Lido di Dante. After having done a preliminary survey of the entire beach, two cross-shore areas with different morphologies and slopes were chosen.

In order to evaluate minor topography changes, very precise surveys were undertaken with a total station. The spacing between measured points was about 30 cm, and special attention was dedicated to the positioning of the surveying rod, to ensure a good accuracy of the data on the vertical dimension.

Moreover, profiles of reference rods were established in order to follow feature migration on the beach. The locations of the rods and bed elevations at their bases were measured during each low tide of the fieldwork period. The disturbance layer was assessed using two different methods: a) green coloured sand was injected at six points along each cross-shore profile (KING, 1951; WILLIAMS, 1971; CIAVOLA et al., 1997); b) rods with a loose-fitting washer were inserted on each of the stacks (ANFUSO et al., 2003). Observations of internal bar structures were carried out along trenches and sediment samples were collected along the cross-shore profile. Moreover, at the Lido di Dante site, fluorescent sand tracers were immersed on the bar crest in order to quantify the residual sediment transport.

At Volano, wave conditions were obtained installing a pressure transducer on a pier, located immediately to the south of the study area. Data were collected as 20 min burst, at a frequency of 4 Hz, at the beginning of each hour. Wave parameters were computed using standard spectral analysis. The transducer was located below low-tide level, in order to ensure continuous recording during the experiment. At Lido di Dante site, offshore waves were measured with an ADCP, and conditions over the bar assessed by a RCM9MKII Aanderaa current-meter recording every 5 min.

In the laboratory, offshore wave data were used to compute the water levels on the intertidal zone, following the methodology of KROON and MASSELINK (2002). The combined effect of wave set-up and wave run-up was calculated with the following equation (HOLMAN, 1986 in KROON and MASSELINK, 2002):

$$R = 0.36 g^{0.5} H_o^{0.5} T \tan \beta$$

where R is the wave run-up height exceeded by 2% of the events, g is acceleration of gravity, *Ho* the deep-water wave height, *T* the wave period and tan*β* is the beach gradient.

RESULTS

Lido di Volano field campaign

Beach morphology

Two cross-shore profiles were studied during the fieldwork (Figures 2, 3). The first area (CS1) is located approximately 300 m northward of the main recreational beach of Volano. At this point, large, slightly oblique, longshore bars are attached to the coast (CIAVOLA and CORBAU, 2002). The intertidal beach was located on the seaward face of the main bar and was approximately 40 m wide. The mean slope was 2%. The second area (CS2) was closer to the beach of Volano. Here the longshore bars were either absent or already integrated into the morphology of the beach, which presents a ridge and swale feature, separated from the upper beach by a small channel. The upper beach has a mean slope of 14%, whereas the lower part is very flat (<1%), and the foreshore reaches 4%. The intertidal beach was 25 m in width.

The intertidal beach was characterised by the presence of alongshore sandbars of small amplitude. On the 14th of January four sandbars were identified. These bars are very similar to the lens described by OWENS and FROBEL (1977) during the post-storm recovery of the beach at Magdalen Island (Canada). They had an average amplitude of less than 10 cm, and wave length ranging from 1 to 7 m. Bar 3, located at –0.2 m/MSL, was the most developed, and amplitude of the bars decreases in size onshore.

These bars had a very steep landward face, testifying an origin related to swash processes and a probable onshore migration (DAVIS et al., 1972; OWENS and FROBEL, 1977). Moreover, the landward face presented a fan-like morphology attesting the swash overtopping. No bedforms were observed on the bars, while small symmetric ripples (A<0.5 cm) were present in-between the bars.

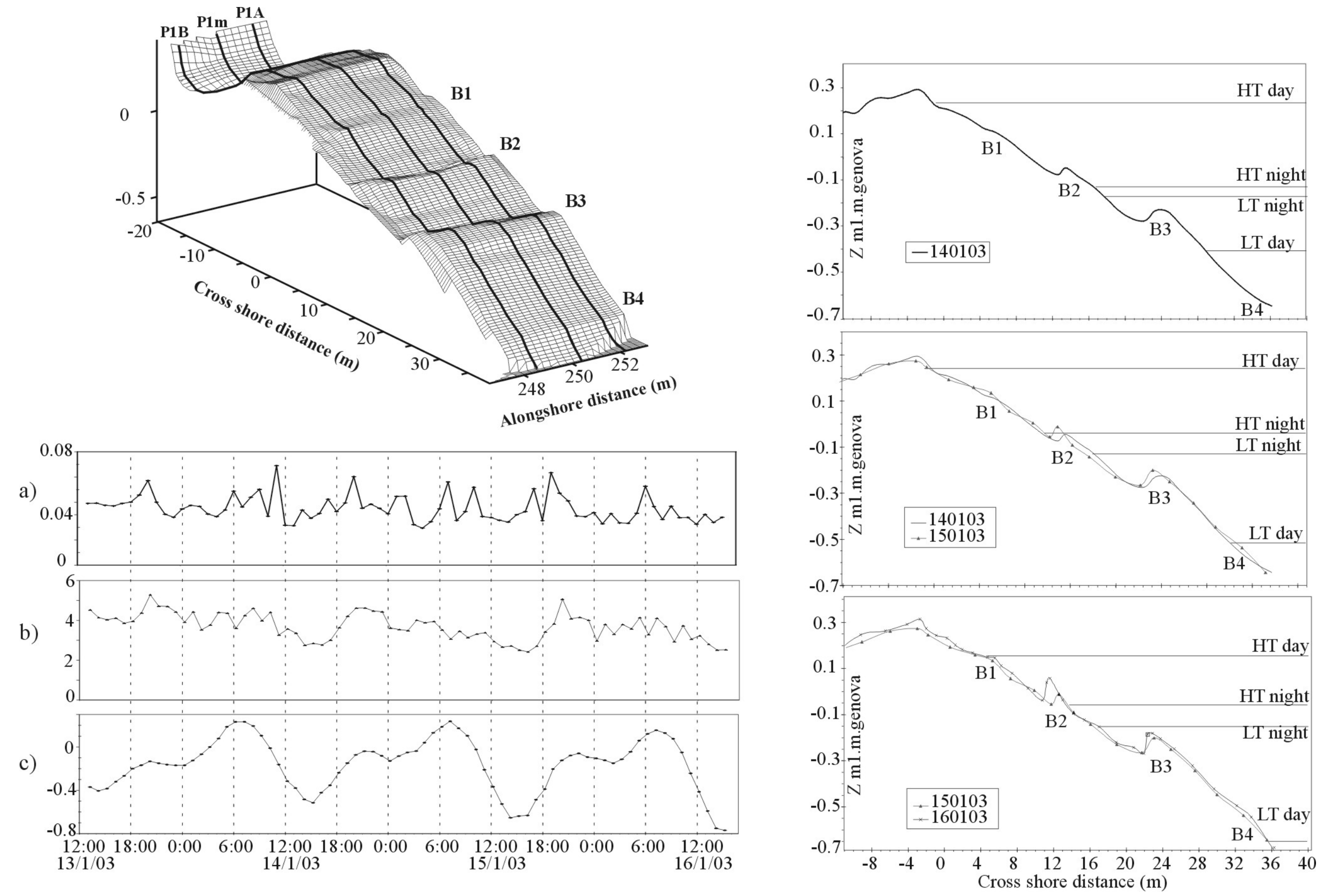

Figure 2. Cross shore profile on Lido di Volano site. Left: 3d topography of the CS1 area, and wave conditions during the fieldwork: a) significative height (m), b) mean period (s), c) water level (m). Right: P1A profile evolution and associated tidal levels.

Hydrodynamics

The tidal water level and waves during the field experiment are shown in Figure 2. Significant wave heights ranged from 0.04 to 0.08 m, with a mean period between 3 and 5 s. Wave crests were generally parallel to the coast.

The fieldwork was undertaken just after neap tides (12th of January) and tidal range was increasing during the field experiment. Tidal curves were very asymmetric, with night tidal ranges reaching 0.1 m, while day tidal ranges were about 0.8-0.9 m. This results in a regime that is almost diurnal.

Morphodynamics

Intertidal bars at both cross-shore transects were surveyed from the 13th to the 16th of January. Morphodynamics of the bars were mainly characterised by an onshore migration, with beach volumes remaining constant (Figure 2).

Despite a very calm wave climate, the microtopography of the beach showed rapid changes. Sand bars were quickly migrating landwards, sediment was transferred from the seaward slope to the landward slip face. This migration seems to be the result of a re-organisation of the bars that become narrower and higher (e.g. B2). The topography of the flattest parts remained unchanged.

Changes in bed elevation (Figure 3) were more pronounced on profile 1, where the slope was less steep than in profile 2. Moreover, there is a strong relationship between the mean slope and the formation of bars. On CS1, where the mean slope is 2%, bars were developing and migrating over the entire intertidal area. The most important changes in topography were related to the bar migration and generally had a limited amplitude (<10 cm).

Internal structures of the main bars of the beach were observed. The large bars were formed by alternate and parallel laminae of fine sand and shell fragments. Laminae were sub-parallel to the beach surface and the lee side of the bar presented a reactivation surface and "avalanche" structures, that recorded landward migration.

The measured values of disturbance depth were very small (less than 1 cm). Taking into account that waves were small, this layer is directly related to swash processes. On the flats between the bars, the mixing layer was either absent or directly related to the presence of small ripples. The swash bars were migrating without any significant sediment redistribution, keeping a constant volume, becoming narrower and narrower. The migration of the swash bars was measured both by profile analysis and direct surveys of their upper limits. Migration rates were calculated for a 24h tidal cycle and values are reported in Table 1.

The migration rate of the upper swash bars, B1 and B2, tended to increase with the tidal range from 13/01 to 16/01 (except for B2 on the 13th to 14th), while the lower swash bars (B3 and B4) decreased the migration rate. This tendency is observed on all the three monitored profiles.

Bar 3 had a tendency to flatten out, with migration rates becoming less evident. This process has been observed on nearshore bars under shoaling waves (SUNAMURA and TAKEDA, 1984). This bar, inundated during almost the whole 24h tidal cycle, could thus have a different behaviour, due to its position on the intertidal area, being similar to a longshore bar.

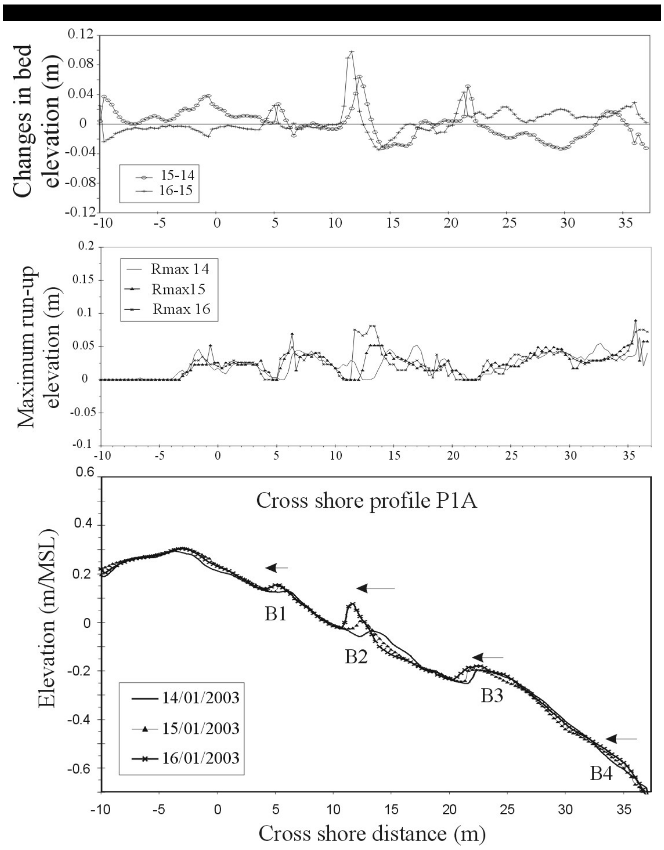

Figure 3: Topography evolution of profile P1A (CS1). Top: changes in bed elevation between successive surveys, middle: maximum run-up levels computed using offshore wave data and local slope, bottom: overlay of 14th , 15th and 16th of January profiles.

On cross-shore area 2, migration rates were measured on bar 2-1 and 2-2 (Table 1). Although bed elevation changes were very small, migration speed appeared to be slightly higher than in profile 1. This could be explained by the morphology of the beach, that tended to concentrate wave action on a limited part of the intertidal area.

As showed in Figure 2, the position of the bars on the beach profile is closely related to the mean water level position during each tidal cycle. The largest morphologies are located at the level of the tides of 12th of January at night, when the slack water level remained at the same position during more than 12h. Moreover, several bars that appeared during the fieldwork are located at an elevation of a standing mean water level.

Another interesting point is that bars are much more developed at the night slack water levels than around the day ones, pointing out the importance of the water level stationarity in controlling the formation and the evolution of these swash morphologies.

To investigate the duration of swash processes over the bars, the maximum run-up was computed using the beach profiles, taking into account the local slope and offshore wave data (Figure 3). Values of maximum run-up are generally low, in relation with incident waves. However, local slopes of the seaward faces can generate a run-up elevation reaching 5 to 10 cm. Despite this run-up being very limited, it can play a significant role on the intertidal zone, especially when the tidal range is null at night.

This maximum run-up elevation was then used to calculate the duration of swash on the crests of each studied bars. Due to the strong asymmetry between night and day tides, the calculation was performed for 24h tidal cycles.

Lido di Dante field campaign

Within the EU Coastview project (ALBERTAZZI et al., 2003), the beach of Lido di Dante is regularly surveyed. A 2 weeks fieldwork was undertaken in April 2003. This straight coast is limited northward by a zone protected by a breakwater, and southward by the Bevano river mouth. The beach is characterized by the presence of intertidal bars with a longshore variability that seems to be correlated with the position of subtidal crescentic bars.

Beach morphology

During the field study, the internal sand bar had already reached the intertidal area, and thus was exposed to swash processes. The intertidal zone was characterized by the presence of a well-developed bar-through system (Figure 4). The intertidal area was 30 m wide. The swash bar has an amplitude of 0.25 m, with a length of 25 m. Mean slope on the seaward face of the bar is about 2%. The bar is strongly asymmetric and the landward face has a gradient reaching 4.5%.

Hydrodynamics

The tidal amplitude during the fieldwork was about 1 m for the evening tidal cycle and 0.5 m for the morning one. Offshore significant wave heights ranged from 0.1-0.4 m, with a mean direction of 80°N (i.e. cross shore). Peak period was about 4 s.

Morphodynamics

Cross shore morphology was surveyed during 4 successive tidal cycles. Morphodynamics of the bar were mainly characterised by an onshore migration of the crest (Figure 4) and the erosion of the

Lido di Volano										*Lido di Dante*		
Profile	Date	Migration in m / 24h				Profile	Date	Migration (m/24h)		Profile	Date	Migration (m/12h)
		Bar 1	*Bar 2*	*Bar 3*	*Bar 4*			*Bar 2-1*	*Bar 2-2*			*main bar*
	13 to 14/01		1.6				13 to 14/01	2.3			16 to 16/04	1.8
P1A	14 to 15/01	0.44	0.73	0.4	3	P2C	14 to 15/01	1.44	0.31	PC	16 to 17/04	0.8
	15 to 16/01	0.57	2	0.42	0		15 to 16/01	0.55	1.2		17 to 17/04	0.8
	13 to 14/01		1.2				13 to 14/01	0.37			16 to 16/04	2.1
P1B	14 to 15/01	0.65	0.4	0.8	2.5	P2D	14 to 15/01	0.73	0.6	P1N	16 to 17/04	1.2
	15 to 16/01	0.9	1.2	0.45	0.5		15 to 16/01	0.47	1		17 to 17/04	1.1
P1m	14 to 15/01	0.4	1.18	1.5	3	P2m	14 to 15/01	0.91	1.04			
	15 to 16/01	0.9	1.05	0.42	0.4		15 to 16/01	0.48	1.56			

Table 1: Migration rates of the swash bars derived from topography and crests surveys (rods).

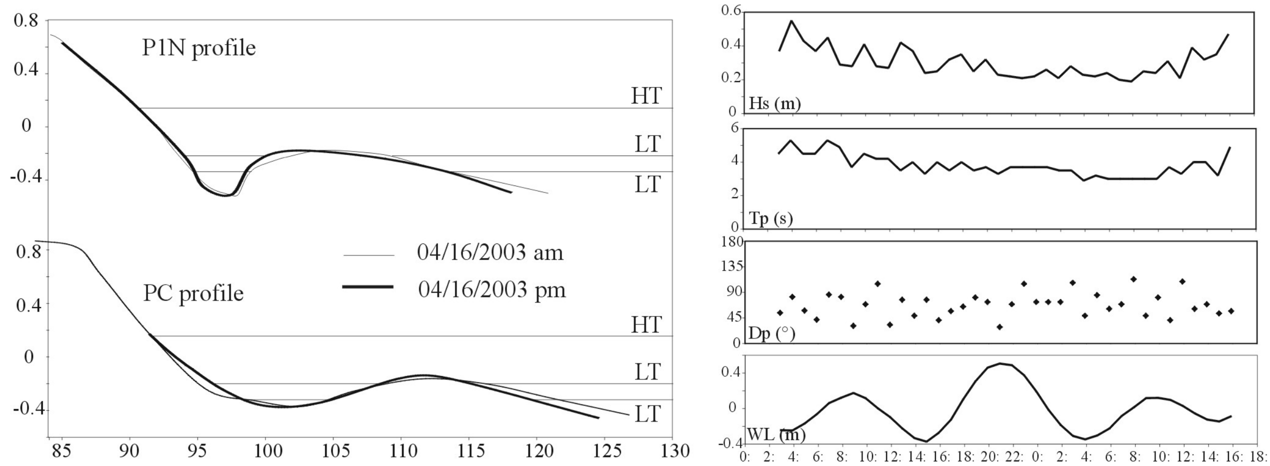

Figure 4. Cross shore profile on Lido di Dante site. Left: profile changes from 04/16 am to pm, and tidal levels (LT: Low tide, HT: High tide); Right: Offshore wave conditions during the survey (significant height, peak period, peak direction and water levels).

berm slope. Sediment was transferred from the seaward slope to the landward slip face of the bar, while sediment eroded on the berm slope was transferred to the channel.

As on the Lido di Volano site, internal structures of the bar were formed by laminae sub-parallel to the beach surface and the lee side of the bar presented a reactivation surface and “avalanche” structures. The measured values of the disturbance depth were very small (1-2 cm). In the channel, observed structures were small ripples (A= 3-4 cm, wavelength= 10 cm), parallel to the beach, attesting the weak longshore component in the channel. However, during the second low tide of the 17th of April, these bedforms in the channel had a low northward orientation, indicating a more efficient drainage during low tide.

Sand tracers immersed at the morning low tide the 16th of April have shown a weak sediment transport over the bar crest, and all tracer was recovered on the lee side of the bar at the successive low tide. A second detection was performed at the low tide of the 17th in the evening. Tracer cloud shown a different behaviour, with a first component directed cross shore toward the channel, and then a longshore sediment transport northwards in the channel.

Migration rates of the bar crests were measured both by profile analysis and direct surveys using rods (Table 1). The migration rates during the first tidal cycle reached 2 m/12h. During the second tidal cycle, with a higher tidal range, migration rates decreased on both transects (0.8 and 1.2 m/12h). The migration rate remained low during the successive tide.

As at the Volano site, bars were subjected to swash processes at low tide levels, and even if the nature of this bar cannot be related to standing water levels, the observed migration processes seems to be linked to these standing periods.

The maximum run-up elevations calculated permitted to compute the duration of swash processes on the bar crests. As the offshore waves remained more or less constant, this duration is mainly related to the tidal curve. When tidal range is low, duration of low slack waters are highest, enhancing the duration of swash on the bar crest (tide 1 and 3).

DISCUSSION

Two different sites of the Northern Adriatic were surveyed during low hydrodynamic conditions. At the Volano site, the structures are formed by the swash, whereas at Lido di Dante, the observed bar results from the attachment of a longshore bar to the coast now exposed to swash processes. Despite this evident difference in bar morphologies, a similar behaviour was observed. During a low wave regime and despite a very weak remobilisation of sand, a consequent migration of the intertidal swash bars was outlined (0.5-3.3 m/day).

As it was already described by previous authors (e.g. SUNAMURA & TAKEDA, 1984), when the inner bar is migrating, wave breaking always occurs on the seaward face of the bar, and sediment is then transported by bores towards the steep landward edge, generating the deposition on the slip-face of the bar. However, here, wave energy was very low, and according to SUNAMURA and TADEKA (1984), no migration should have occurred when the bars were immersed.

At Lido di Volano, the position of the swash bars is always related to the slack water levels. The bigger bars (B2, B3) developed in the middle of the intertidal area at night, when the water level remained stable for a long time. Consequently, these bars show the highest migration rates. All the observed dynamics seem to be related to swash processes and with the duration of their action on the bars (i.e. slack water level periods).

As the tidal range increased during the survey, swash bars appeared all over the intertidal area at slack water levels, and migrated according to their exposure to swash processes. On cross-shore profile 2, the steep slope of the lower beach might have generated a dissipation of energy in a very limited space, where the swash bars begun to appear. As tidal range increased, the flattest intertidal zone was not directly exposed to swash processes. No further swash bars were developed because of the low beach gradient and the presence of the lower bars protecting the area. In this case, the pre-existent morphology played an important role on exposure to swash processes. Moreover, as stated by HAYES (1972), beach gradient could play a significant role in bar migration. For similar tidal levels, migration rates on CS2 (highest beach gradient) was much more important than on CS1 area.

SALLENGER and RICHMOND, 1984, GREENWOOD (2003) described high frequency vertical oscillations of the seaward face of a swash bar in more energetic environments (breaker height until 4m). The sediment-level oscillations were progressive landward, but involved a net seaward sediment transport. The features described at the Volano site have a similar morphology.

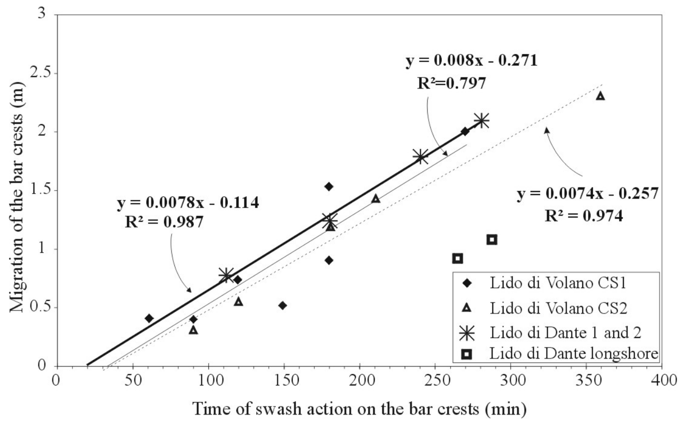

Figure 5: Relationship between duration of swash processes over the crests and bar migration rates.

However, they do not occur at the same time scale, and clearly show an onshore migration, rather than small vertical oscillations. This particular behavior could result from the very low wave energy during our measurements, and the very long slack water period of the second tide. In addition, some important differences are notable: i) the migration involves a net sediment transport, as shown by tracer measurements and the constant volume of Volano's bars. This sediment transport is clearly in the direction of migration (i.e. onshore) as described for swash bars, ii) they cover all the intertidal area, and at the CS1 area, 4 of these features were developing on the seaward face of a main sand bar. As the Skallingen sand bed oscillations (GREENWOOD et al., 2003), it is thought they could reflect pulses of sand that progress landward every tidal cycle and contribute to the accretion and migration of the main bar. However, the main bar was not overtopped during our fieldwork period to confirm these assumptions.

For both Lido di Dante and Lido di Volano sites, the migration rate versus the duration of swash processes over the crests was plotted (Figure 5). Despite different slopes and morphologies of the bars, and differences in wave and tidal conditions, a very good correlation was found. Migration of the bar seems directly correlated with the duration of swash over the crest (i.e. standing levels).

At the Lido di Dante site, the migration rates during the third tide (Lido di Dante longshore data points on Figure 5) were not taken into account in the regression analysis. The duration of swash was longer, but migration rate lower. This could be explained by the increase of longshore processes during this tidal cycle. A part of sediment transported onshore by the swash is then transported by longshore currents in the channel and does not participate to the onshore migration of the bar. In such systems, increase of the longshore current resulting from changes in offshore wave angle results in the decrease of bar migration rate.

At the Volano site, an increase of the migration rate was observed as the tidal range increased. As it was already observed in more energetic environments (e.g. KROON, 1994), the onshore displacement of the low tide slack water levels permitted to maintain an elevated migration rate of the bars.

At the view of our results, as on intertidal bars at other sites (KROON and MASSELINK, 2002), it seems to exist a threshold of swash duration to obtain a significant migration of the bar. From the field measurements, this threshold would be about 30-35 min at the Lido di Volano, and 20 min at the Lido di Dante beach, but it is certainly related to the volume to be deposited on the landward side of the bar, before a migration of the crest can be observed, and thus depends on local characteristics: gradient of seaward and landward slopes, grain size, swash infiltration/exfiltration, although this is likely to be unimportant for fine to medium sand beaches (BUTT et al., 2000).

Bars that are not affected anymore by swash processes have low migration rates or remain stable and tend to flatten. Their morphodynamics are similar to those of inner longshore bars (SUNAMURA and TAKEDA, 1983; LIPPMAN et al., 1993; PLANT et al., 1999) or subtidal bars (DAVIS and FOX, 1972).

CONCLUSIONS

The work described in this paper reports on field experiments focussed on sand bar migration processes in an intertidal area (microtidal). Significant morphological changes were observed, despite the virtual absence of waves. Volano's sand bars are intertidal features behaving like swash bars. Their landward migration is strictly related to the duration of swash processes over the bar, that was particularly important in this asymmetrical tidal regime.

Experiments on a different swash bar at Lido di Dante seem to confirm such a relationship between bar migration and swash action. However, the migration rate decreases when longshore currents appear, and further experiments are required to take into account the longshore component in the migration process.

Due to specific wave and tidal conditions, the Northern Adriatic Sea constitutes an exceptional field site to study the formation and the migration of swash bars under particular tidal regimes.

In order to fully understand the behaviour of suches small swash bars, and their eventual relationship with swash zone oscillations, short-term measurements would be necessary, as well as a longer period of survey. However, the present preliminary study points out the important dynamics of microtidal beaches in the virtual absence of waves.

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