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MORPHODYNAMICS OF SLIGHTLY OBLIQUE NEARSHORE BARS AND THEIR INFLUENCE ON THE CYCLE OF NET OFFSHORE BAR MIGRATION

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Abstract

Slightly oblique nearshore bars are common features on most barred beaches worldwide. However, their great longshore extension requires large spatial scale data sets and thus they have been poorly studied. Our study is based on a large set of data (LiDAR, bathymetric profiles and aerial photographs) to accurately describe the morphology and multi-annual dynamics of a system of slightly oblique bars present on a barred beach of the Gulf of Lions (Mediterranean Sea, France). Slightly oblique bars are characterized by a down-drift longshore gradual increase of their distance from the shoreline over dozens of kilometres, forming an angle of 3-4° relative to the shore. Thus, at any time, the bar is in a different phase of the net offshore migration (NOM) cycle according to its longshore extension. For instance, a single bar is in the emergence phase of the cycle at its proximal end near the coast, in the phase of seaward migration where it exhibits transition/switching state from on- to offshore position and finally in the decay phase at its distal end where its disappears. On a multi-annual timescale, net offshore migration (NOM) of slightly oblique bars results in an up-drift displacement of the bar pattern, with rates that can reach several metres per day. Thus, a longshore time lag appears in the NOM cycle when the bar is observed on separate cross-shore bathymetric profiles. These bars are common to many barred beaches worldwide where NOM cycles have been identified and further research are requiring to improve our knowledge of these features.

Keywords: Slightly oblique bars; Net offshore migration; phase of bar cycle; up-drift displacement; longshore time lag.

1. Introduction

On a multi-annual scale, longshore sandbar systems generally demonstrate a cyclic evolution characterized by a seaward migration (Kuriyama and Lee, 2001; Plant et al., 1999; Ruessink and Kroon, 1994; Shand et al., 1999; Wijnberg and Terwindt, 1995). During this Net Offshore Migration (NOM) cycle, the offshore decay of the outer bar results in larger wave energy across the inner bar that drives its rapid seaward migration and the emergence of a new bar near the shoreline (Fig. 1). Most barred beach worldwide, with a large panel of environmental parameters, are characterized by NOM cycle (e.g. Black Sea, Romania (Tătui et al., 2011; Tătui et al., 2016); Mediterranean Sea, Egypt (Khafagy et al., 1992), France (Aleman et al., 2013; Certain and Barusseau, 2006), Spain (Guillén and Palanques, 1993); Pacific Ocean, Japan (Kuriyama and Lee, 2001; Yuhi et al., 2016), USA (e.g. Ruggiero et al., 2016); Atlantic Ocean, the Netherlands (Ruessink and Kroon, 1994; Wijnberg and Terwindt, 1995), USA (e.g. Lippmann et al., 1993); Tasman Sea, New Zealand (e.g. Shand, 2000)).

Cycles of net offshore migration were generally defined as alongshore coherent (Wijnberg and Terwindt, 1995). Nevertheless, alongshore non-uniformities were previously identified on a large spatial scale of ten kilometres (Shand and Bailey, 1999) such as slightly oblique nearshore bars forming an angle of 3-4° with the shoreline behind the proximal (landward) end and the distal (seaward) end of the bar (Guillén and Palanques, 1993; Kroon, 1991; Kroon, 1994; Lippmann et al., 1993; Ruessink and Kroon, 1994; Shand et al., 1999; Yuhi et al., 2016). The transition zone, being often related to bar switching, is located between the nearshore and offshore position of the bar and can extend over distances of hundreds of metres to several kilometres (Shand, 2003; Shand and Bailey, 1999; Shand et al., 2001; Walstra et al., 2015; Wijnberg and Terwindt, 1995).

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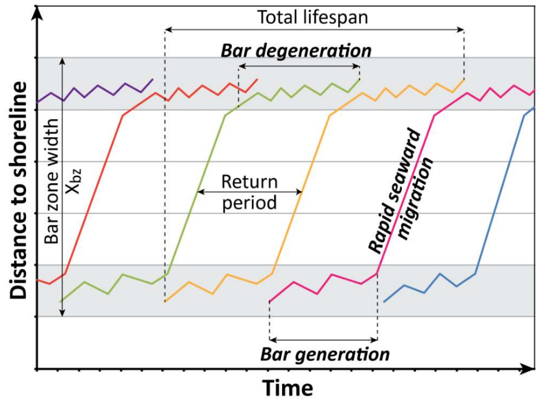

Figure 1: Parameters and terms used to define a NOM cycle. The total lifespan of the bar corresponds to the full duration of a NOM cycle. The return period is the time between the passage of two consecutive bars at the same position. The NOM cycle goes through three phases or stages: bar emergence near the shore, rapid seaward migration and offshore bar decay (adapted from Grunnet and Hoekstra, 2004).

Several studies have addressed the physical processes that govern the morphodynamics of bar switching, and these phenomena are still not fully understood. Switching episodes appear to be triggered by the association of shore-oblique storm events and strong longshore currents (Shand et al., 2001) or to be associated with a specific antecedent morphological configuration combined with storm conditions (Walstra et al., 2015). A longshore "migration" of the transition zone over several kilometres was observed with a rate of up to 11 m/day in the Ebro Delta in Spain, 10 m/day in New Zealand and 3 m/day in the Netherlands (Guillén and Palanques, 1993; Ruessink and Kroon, 1994; Shand et al., 2001; Wijnberg, 1995; Wijnberg and Terwindt, 1995).

The description of sandbar morphology can be obtained by several technologies such as echo sounder profiles (Certain and Barusseau, 2005; Tătui et al., 2016; Walstra et al., 2016; Yuhi et al., 2016), LiDAR surveys (Aleman et al., 2015; Aleman et al., 2013; Aleman et al., 2011), photographic and satellite imagery (Barusseau and Saint-Guily, 1981; Lafon et al., 2004) or video records (Almar et al., 2010; Lippmann and Holman, 1990; Wijnberg and Terwindt, 1995). Spatial (alongshore regularity of profiles and observations), temporal (alongshore regularity of time records) or accuracy specific limitations of these data sets explain why little attention has been focused on bar switching and/or the dynamics of slightly oblique bars which stretch over tens of kilometres.

In this context, the aim of the present paper is (1) to accurately describe slightly oblique bar on a large spatial scale (a dozen of kilometres), (2) to define the multi-annual longshore dynamics of the sandbar morphology in plan view and (3) discuss their relation with the NOM cycle. Therefore, a large area of swell-dominated coast of the Gulf of Lions (Mediterranean Sea, France) was investigated on long-term and large spatial scales using a large mixed data set (LiDAR, echo sounder profiles and aerial photographs).

2. Study Area

The Gruissan beach, located in the Gulf of Lions (Mediterranean coast of SW France), extends over 10 km of sandy coast from Gruissan to Saint Pierre-la-Mer. Several coastal structures are located on this coastline: Gruissan harbour, the jetties of Mateille lagoon and Narbonne Plage harbour (Fig. 2B). The net annual longshore sediment supply is southward, with a volume of between 3,000 and 40,000 m^3/yr (Durand, 1999). The D_{50} particle size distribution ranges from 0.130 to 0.353 mm and the total sand volume is relatively constant with an average of 1432 m^3/lm (Brunel et al., 2014; Raynal et al., 2015). The nearshore zone displays a system of two well-developed sandbars (Fig. 2B). According to Wright and Short (1984), the typology of the inner bar generally corresponds to a "Rhythmic Bar and Beach" (RBB), while the outer bar is Dissipative (D) to "Longshore Bar and Trough" (LBT) (Aleman et al., 2015; Aleman et al., 2011). The coast is a microtidal (tidal range < 0.35 m at mean spring tide), wave-dominated environment (low mean significant wave height, with seasonal energetic storms) is characterized. The averaged wave incidence during extreme events (99th percentile) is -1.1° (Gervais, 2012).

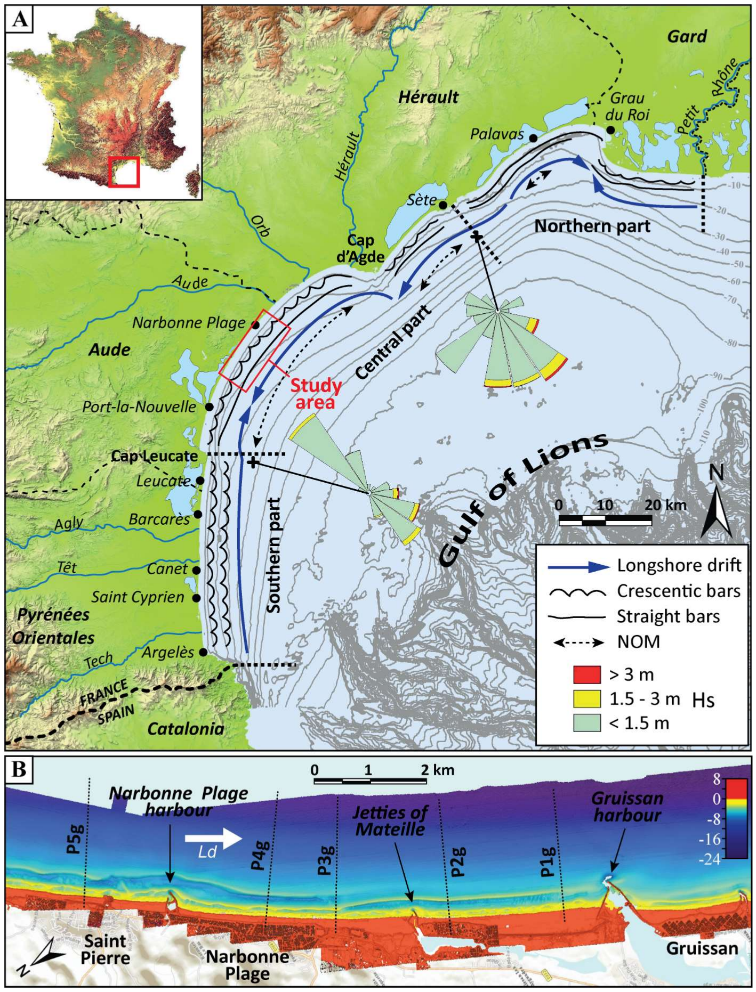

Figure 2: (A) Morphobathymetric map of the Gulf of Lions. Roses indicate wave direction and height recorded by the Leucate and Sète buoys. (B) Map of Gruissan beach according to LiDAR survey with bathymetric profiles location (white arrows indicate longshore drift).

Table. 1: Datasets used in this study

Data set	Alongshore coherence	Date available
LiDAR	3D continuous	2009, 2011
Aerial photographs	2D continuous	1986, 1989, 1992, 1995, 1998, 2003, 2008
Bathymetric profiles	2D segmented	1988*, 1989*, 1990*, 1997*, 1998*, 1999*, 2001, 2002

* *indicates that all profiles are not available*

3. Methods

Multiple data sets were used to investigate the inter-annual morphodynamics of the sandbar systems: LiDAR bathymetric surveys, bathymetric profiles and aerial photographs (Table 1). Five bathymetric profiles were surveyed (Fig. 2B) annually or every two years from 1984 to 2004 (Table 1) with a vertical accuracy of ± 5 cm and a horizontal accuracy of 1 m. Then, two LiDAR surveys (Table 1) were implemented in 2009 (LADS Mk II) and 2011 (LADS Mk II) to provide an alongshore continuous view of the nearshore morphology (Fig. 2B) with a minimal spatial resolution of approximately 5 m and a vertical accuracy of approximately 30 cm. This data set is supplemented by aerial photographs georeferenced using a Geographic Information System (ArcGIS 10) with an accuracy of ± 1 m. The aerial photographs are available every 3-5 years from 1986 to 2008 (Table 1). On each photograph, as a result of the water transparency, it is possible to identify the morphology of the nearshore bars.

The bar position is assessed by drawing the bar systems for all available dates in ArcGIS 10. The determination of the longshore continuity of the bars using LiDAR or aerial photographs helps link the crests of the bars on the different bathymetric profiles, while avoiding errors, and allows an accurate identification of each bar generation. Uncertainty of bar crest position is about ± 5 m that allows to investigate the longshore bar mobility at large temporal and spatial scales. For all the profiles, the NOM parameters are calculated (the return period, the duration of the rapid seaward migration phase and the average migration rate) (Fig. 1).

The LiDAR 2009 profiles spaced at alongshore intervals of 200 m are used to extract instantaneous morphometric parameters of the bars. The different parameters computed in this way are presented in Fig. 3. The bar zone width, X_{bz}, corresponds to the cross-shore distance between the most onshore and offshore bar crest positions during the multi-annual bar cycles (Fig. 1) observed on the historical profiles. The nearshore slope β is also derived from the LiDAR 2009 profiles between the coastline and 10 m water depth. Median grain size D_{50} of the shoreface is calculated from sediment samples collected every kilometre over the inner bar, the outer bar and the lower shoreface (Aleman et al., 2015).

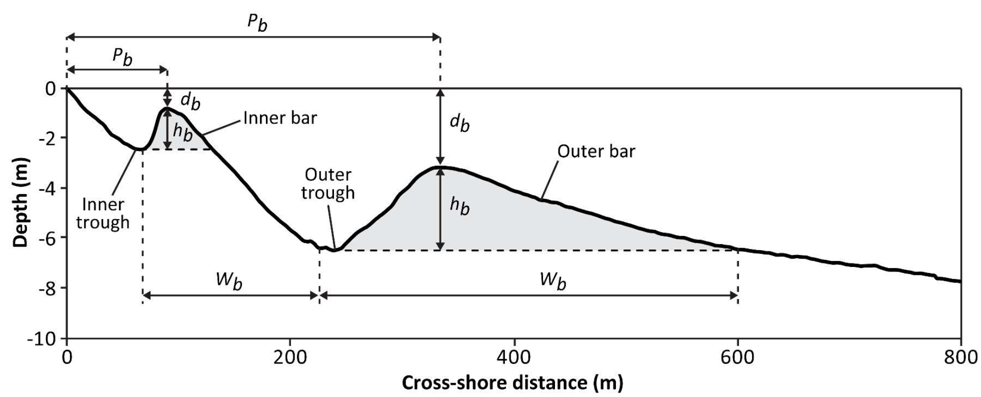

Figure 3: Conceptual diagram displaying the different bar parameters used in this study. d_b: depth of bar crest (m); P_b: bar position relative to the shoreline (m); h_b: bar height (m); W_b: bar width (m).

4. Results

4.1. *Sandbar morphology*

On the nearshore of Gruissan, three longshore bars are present in 2009 on the LiDAR bathymetry (Fig. 4). From NE to SW, the outer bar ($\overline{P_b}$ = 450 m and $\overline{d_b}$ = 4.2 m) peters out in the central part of the area. This disappearance is marked by an abrupt decrease of h_b and W_b (from 3.2 and 470 m at km-4.0 to 0.3 and 150 m at km-5.2 respectively). The inner bar ($\overline{P_b}$ = 140 m between km-0.0 and 4.4) is seen to shift over a short longshore distance (~1 km) to an offshore position ($\overline{P_b}$ = 310 m between km-5.2 and 9.0), in the sector where the outer bar disappears, becoming deeper ($\overline{d_b}$ from 1.7 to 2.7 m), higher ($\overline{h_b}$ from 1.5 to 2.7 m) and wider

($\overline{W_b}$ from 83 to 210 m). Close to the shore, a new inner bar appears (km-4.8) in the SW part of the area ($\overline{P_b}$ = 70 m, $\overline{d_b}$ = 1.1 m, $\overline{h_b}$ = 0.6 m and $\overline{W_b}$ = 47 m). The nearshore slope oscillates around 0.47° until km-1.4, before decreasing over a short distance (0.4 km) and staying around 0.44-0.45° until km-7.4 and finally gradually increasing up to 0.51° over the last 1.6 km. The bar system width is relatively constant between 370 m at km-0.0 to 285 m at km-9.0, with a maximum at km-4.6 (X_{bz} = 510 m). Sediments are fine ($\overline{D_{50}}$ = 170 µm) with little variations (ΔD_{50} = 65 µm).

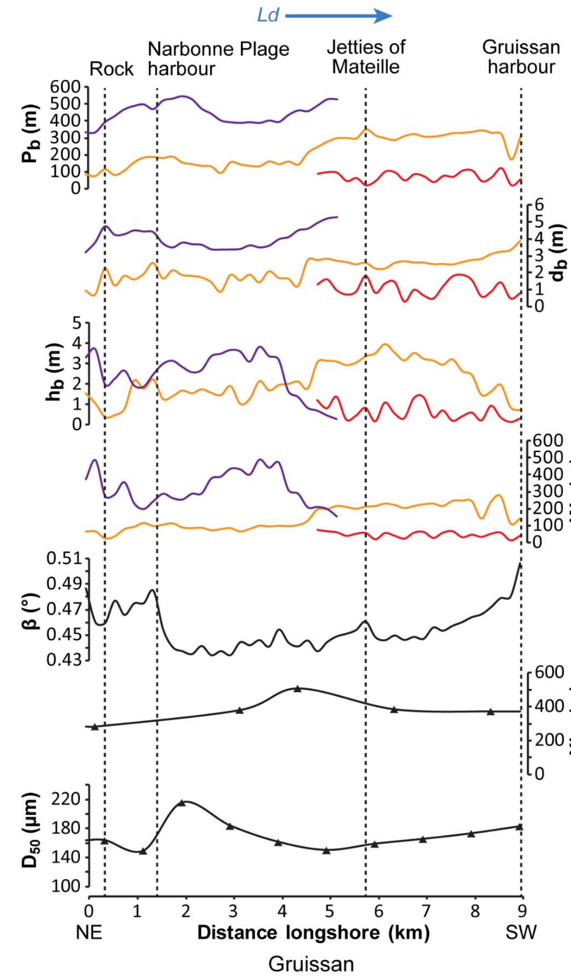

Figure 4: Longshore evolution of morphological parameters (LiDAR data 2009) at Gruissan (left) and Sète (right). P_b: bar position relative to the shoreline (m); d_b: depth of the bar crest (m); h_b: bar height (m); W_b: bar width (m); β: nearshore slope (°); X_{bz}: bar zone width (m); D_{50}: median sediment size (µm).

Table 2: Average of the bar parameters (LiDAR 2009) in the three degrees of NOM cycle. d_b: depth of the bar crest; P_b: bar position from the shoreline; h_b: bar height; W_b: bar width.

Phase of NOM cycle	**P_b**	**d_b**	**h_b**	**W_b**
	(m)	*(m)*	*(m)*	*(m)*
Emergence	86	0.9	2.9	100
Transition/Switching	227	2.2	7.2	210
Decay	458	4.2	6.9	385

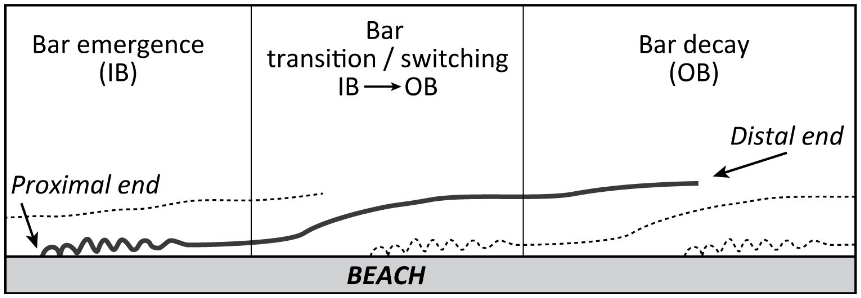

Figure 5: Schematic diagram showing different instantaneous phases of the NOM cycle of a slightly oblique bar (continuous black line) according to its longshore extension (emergence, transition/switching and decay).

These results reveal that bars are characterized by a slight obliqueness with respect to the shoreline (average angle of 2-4°) over about 10 km, from a position close to the shore (proximal end) to an offshore position (distal end) (Fig. 4). At any time and according to its longshore extension, the bar is therefore in a different phase of the NOM cycle (Fig. 5 and Table 2): (1), the bar is in an emergence phase at its proximal end near the shore where it is small, narrow, shallow and displays small crescents. (2) Then, the bar position shifts increasingly seaward, over a short longshore distance of about 1 km (switching, Fig. 4) or more progressively, to occupy an external position where it becomes wider, deeper and higher. (3) Finally, the bar is in a decays phase of the bar cycle at its distal end, where the bar is largest and deepest and gradually disappears alongshore.

4.2. Longshore displacement of the slightly oblique bar pattern

Five generations of bars, denoted from the oldest (bar 1) to the most recent (bar 5), are identified between 1984 and 2012 on the Gruissan shoreface using combination of aerial photographs, LiDAR and bathymetric profiles (Fig. 6). 28 years analysis of the bar position reveals an apparent up-drift propagation of the slightly oblique bars system, which is highlighted by the longshore displacement of the proximal (i.e. connected to the coast) and distal (i.e. offshore) ends of the bars (Fig. 6, only the bar position of most suitable dates are presents here for sake of clarity). For instance, the proximal end of bar 3 moves alongshore from SW to NE between 1986 and 1995, before leaving the study area in the following years. The distal end of this bar first appears in the area in 2003 and move to the NE over a distance of almost 4 km until 2009. Thus, in 23 years (1986 to 2009), the slightly oblique bar 3 has passed through the entire study area (10 km) by moving NE in the opposite direction to the main longshore drift, yielding rates of between 850 and 1500 m/yr (according to the distal and proximal ends displacement).

4.3. ***Net offshore migration of the bars***

Multi-annual bathymetric profiles clearly show the three phases of the NOM cycle (Fig. 6). First, a shallow inner bar close to the shore migrate slowly offshore with some periods of onshore migration (emergence phase), such as the bar 2 between 1988 and 1992 on the profile P3g. Then, the bar migrates quickly offshore (phase of rapid seaward migration), at most in 5 years between 1992 and 1997 for the bar 2. Finally, the bar reaches its farthest and deepest position with some low alternation of on- and off-shore migration before its complete disappearance (decay phase), as shown the bar 2 between 1997 and at most 2008 on the profile P3g (Fig. 8). The irregular frequency of the bathymetric profiles do not allows to accurately define the NOM parameters. However, we can estimate the duration of the seaward migration up to 10 years for the bar 2 and 3. The bar 3 shows that the emergence phase lasts longer than 15 years and the decay phase more than 6 years for the bar 2.

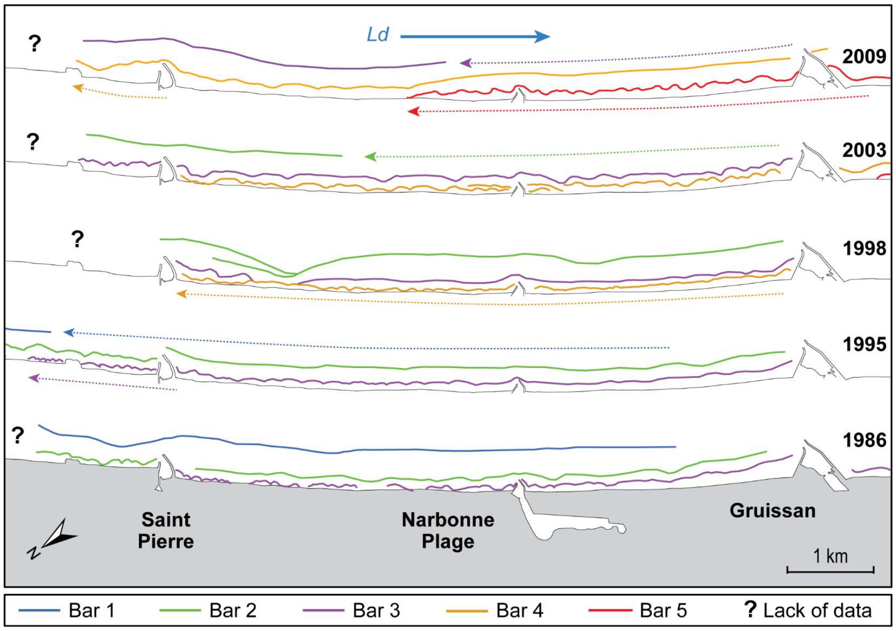

Figure 6: Morphological evolution of the nearshore bar systems on the Gruissan shoreface determined from aerial photographs and LiDAR surveys adjusted with bathymetric profiles (for clarity, data from only 5 dates are shown). Each colour indicates the same bar from one year to another. Dashed arrows indicate the displacement of the bar pattern. Blue arrows indicate the dominant longshore drift (*Ld*)

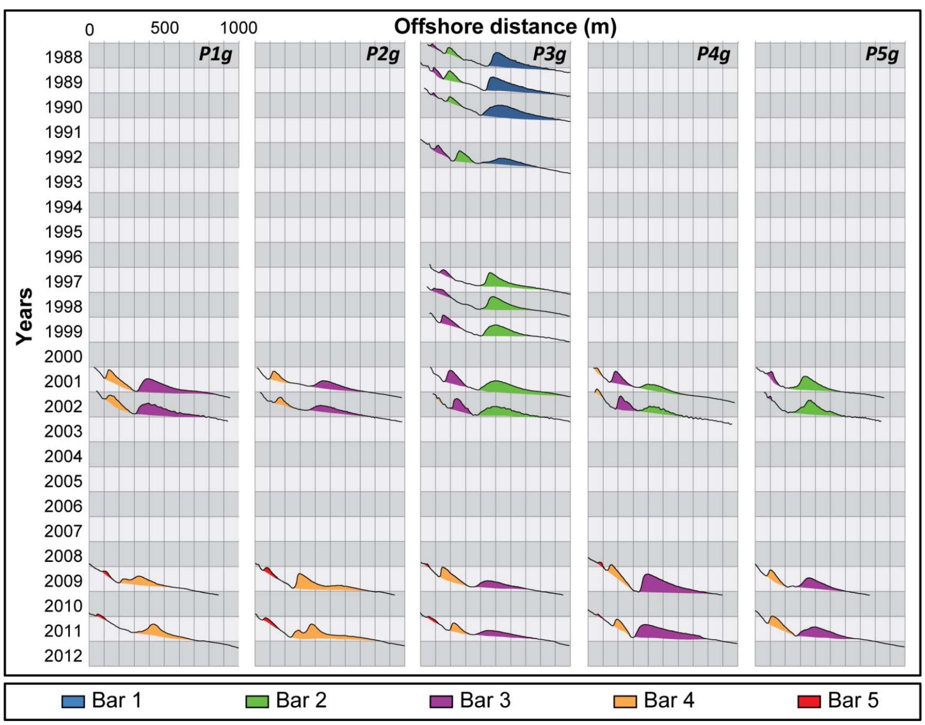

Figure 7: Bathymetric profiles of Gruissan shoreface (P1g to P5g) from 1988 to 2011. Each colour indicates the same bar from one year to another.

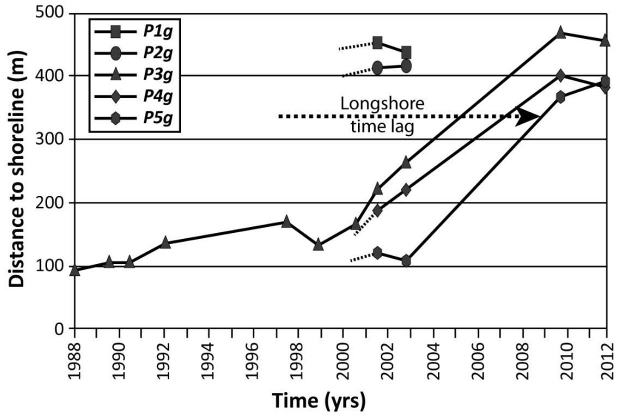

Figure 8: Bar crest position of the bar 3 between 1984 and 2011 extracted from bathymetric profiles on Gruissan shoreface (P1g to P5g). The bar obliquity causes a longshore time lag of the occurrence of seaward migration phases.

4.4. *Influence of slightly obliqueness of the bars on the NOM process*

The NOM cycles identified on the set of bathymetric profiles are classic in view of the literature, with decay of the outer bar, offshore migration of the inner bar and the emergence of a new inner bar close to the shore. However, the cycle is subject to a longshore time lag due to the slight obliqueness of the bars clearly identifiable on the Fig. 8. Indeed, we can estimate a longshore (from SW to NE) time lag of at least 12 years for the rapid seaward migration of the bar 3 between the P1g and P5g profiles (Fig. 8).

These results allow to propose a conceptual scheme highlighting the relation between NOM cycles and bar obliquity (Fig. 9). At the instant T0, the bars on the bathymetric profiles P1 and P2 are in different phase of the NOM cycle due to the slightly obliqueness of the bars. This obliquity generates a longshore time lag of the seaward migration over time (T1 and then T2). The net offshore migration of slightly oblique nearshore bars results in an up-drift displacement of the bar pattern that can be observed on large-scale bathymetric surveys (Fig. 9).

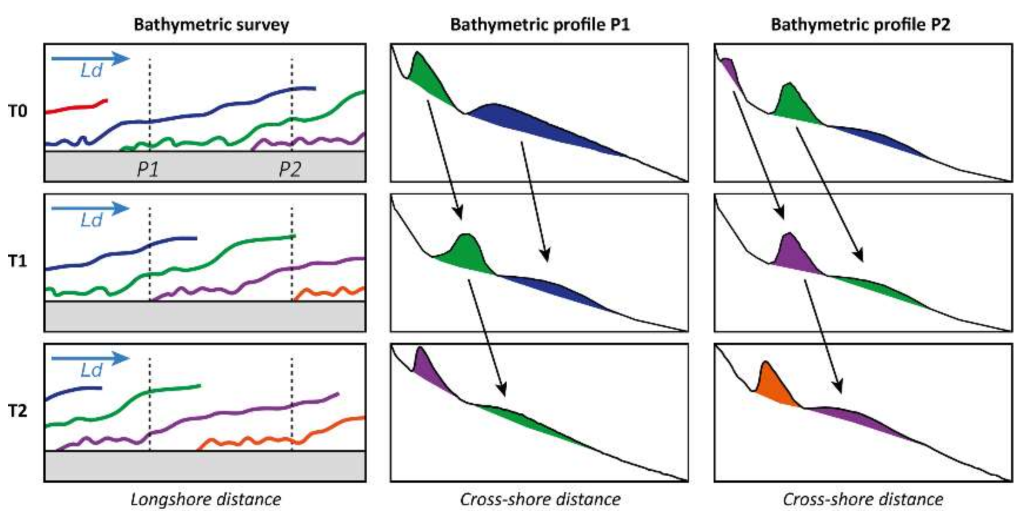

Figure 9: Correspondence between the longshore displacement of slightly oblique nearshore bars on a bathymetric survey and the cross-shore bar migration on a bathymetric profile. The bar is in different phases of the NOM cycle on the P1 and P2 profiles. Blue arrows indicate the dominant longshore drift (Ld).

5. Conclusion

Slightly oblique nearshore bars are frequently identified on barred beaches worldwide with NOM behaviour as per the literature, but they have been little studied because of their wide longshore extent. Using a multiple data sets with a large spatial coverage, the present study describes accurately the morphology and dynamics of these bars on a microtidal barred beach of the Gulf of Lions (Mediterranean Sea, France). The slightly oblique bars are characterised by a longshore gradual increase of their distance from the shoreline over dozens of kilometres in down-drift direction, forming an angle of 3-4° relative to the shore. The longshore transition between the on- and off-shore position of the bar can occurs over short distance such as a switching previously described in the literature. Due to its obliqueness, the bar is in different phase of the NOM cycle according to its longshore extent, from the emergence phase at the proximal end near the shore to the decay phase at the distal end offshore where it disappears. Thus, the occurrence of the NOM cycle is subject to a longshore time lag. Moreover, the seaward migration of the system causes an up-drift displacement of the slightly oblique bar pattern. Physical processes that govern the formation and dynamics of the slightly oblique bar still poorly understood and require further research.

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