Formation and migration of transverse bars along a tidal sandy coast deduced from multi-temporal Lidar datasets

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A field of long-crested transverse bars was monitored from a 2.5-year series of topographic Lidar surveys in the vicinity of a tidal inlet on the macrotidal (mean spring tidal range = 7 to 12 m) west coast of Cotentin (Normandy, France). The bar field, the alongshore extent of which is about 1.8 km, is composed of a total of 8 bars with lengths varying from 320 m to 1300 m and mean heights comprised between 0.5 m and 2.5 m. Bar cross-sections are variable between bars and for a single bar, and also over time. The surveys show a consistent northward migration of the bars at a mean rate of about 2 m/month, but the rate is larger in winter than in summer. The Lidar observations show that the tidal inlet, located at the southern limit of the bar field where the bars start forming, comprises a large sediment platform that acts as a source of sand for the bars. The ebb jet debouching from the inlet is deflected northward by the ambient strong shore-parallel tidal currents in this large tide-range setting, and this may be the primary mechanism leading to the emplacement of the bars. Smaller wave-formed swash bars that further feed the development of these large transverse bars have also been observed. Monitoring of bar migration in the course of six consecutive spring tides with fair-weather conditions showed that strong spring tidal currents are sufficient to drive bar mobility in the absence of waves. Storm wave resuspension of sand is thus expected to enhance bar mobility rates, as shown by the higher rates of winter bar migration compared to the summer rates. The ebb jet explains the slower bar migration rates at the vicinity of the inlet, these rates increasing with distance northward of the inlet as the tidal currents become unimpeded. The main difference between these macrotidal transverse bars and their counterparts in microtidal settings resides in these strong tidal currents that are the essential driver of bar migration, unlike the wave-driven migration of microtidal bars. The large tidal range, in conjunction with storm wave activity, also induces longshore and seasonal variability in bar morphology. The transverse bars of Normandy appear to be inscribed in a sand circulation system involving the west Cotentin coast, the large ebb tidal delta from which they are formed, and the central Cotentin embayment where they are ultimately incorporated into the nearshore sand pool. Longer-term field hydrodynamic monitoring and modelling will be required in order to further elucidate the mode of formation of these transverse bars.

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1. Introduction

Transverse bars, also sometimes termed “finger bars”, are sedimentary features of the surf zone and nearshore area. Shepard (1952) defined these features as bars oriented perpendicular to, or at a high angle to, the shoreline and having a relatively short length scale. It is important, at the outset, to distinguish between long-crested bars (Ribas and Kroon, 2007) with a typical length scale of 10² to 10³ m, which are more or less semi-permanent to permanent inner shelf to surf zone transverse bars, and the smaller, more ephemeral transverse bars (typical scale of 10¹ m to 10² m) that are limited to the surf zone (e.g., Greenwood and Davidson-Arnott, 1979). Examples of short-crested transverse bars have been described from wave-dominated open coasts, such as the US coast of North Carolina (Konicki and Holman, 2000; Schupp et al., 2006) and the Dutch coast (Ribas and Kroon, 2007; Ribas et al., 2011, 2012). Small transverse bars have also been identified in low wave energy estuaries, lakes and sheltered embayments (e.g., Carter, 1978; Khabidov, 2001; Eliot et al., 2006). Long-crested transverse bars appear to be rare features and, to our knowledge, have been reported only from the microtidal coasts of...
Massachusetts (Goud and Aubrey, 1985), and Florida (Tanner, 1960; 2011, 2012), based on linear instability analysis. Khabidov (2001) and Garnier et al. (2006), and more recently by Ribas et al. organised mechanisms in the surf zone. Models of self-organised formation of crescentic and transverse bars may result from self-

reported rates of 1.75 m/month (Gelfenbaum and Brooks, 2003) to rates can be higher at shorter timescales (days to a month) with 40 m/day in North Carolina (Konicki and Holman, 2000). In contrast, some systems appear to be quite immobile at timescales of years to a decade, as Niedoroda and Tanner (1970) and Bruner and Smosna, 1989; Khabidov, 2001; Eliot et al., 2006). In low wave-

energy environments (modal wave heights of few tens of centimetres and a mean tidal range less than 1 m) as along the west-central coast of Florida (Niedoroda and Tanner, 1970; Gelfenbaum and Brooks, 1998, 2003), the bars are generally larger in height, between 0.2 m and 2.1 m, and are not linearly aligned across-shore. Bar heights are lower close to the shore and at the seaward extremity, and maximum in the middle part (Gelfenbaum and Brooks, 2003). Their cross-shore extensions can vary from 100 to 600 m, but, when sediment supply is important, such as close to an inlet, they can attain 3500 m. Transverse bars on moderate wave-energy coasts (modal wave heights of about 1 m) are characterised by wavelengths ranging from 10 m to 360 m, and cross-shore lengths of between 10 and 200 m (e.g., Konicki and Holman, 1996, 2000; Ribas and Kroon, 2007), resulting in their exten-

sion into relatively deep waters. The foregoing observations concern only microtidal environments with mean tidal ranges lower than 1.6 m. No observations in higher tidal range environments have, thus far, been reported in the literature.

Niedoroda and Tanner (1970) suggested that a combination of wave shoaling, induced by refraction caused by random small initial irregularities on the sea bed, and an along-crest sediment circulation was responsible for the formation and maintenance of transverse bars. Falqués et al. (2000) and Caballero et al. (2002) suggested that the formation of crescentic and transverse bars may result from self-

organisation mechanisms in the surf zone. Models of self-organised transverse bar formation have also been proposed by Ribas et al. (2003) and Garnier et al. (2006), and more recently by Ribas et al. (2011, 2012), based on linear instability analysis. Khabidov (2001) and Garnier et al. (2012) have also suggested that tidal flows, longshore currents or wind-wave processes, alone or in interaction, may be re-

sponsible for these forms. Goud and Aubrey (1985) and Gelfenbaum and Brooks (2003) observed that tidal currents alone did not suffice to move transverse bars and that storms passing in the vicinity also served as drivers of bar migration. Apparently, there is no single mechanism of transverse bar formation and, in agreement with Gelfenbaum and Brooks (2003, p.274), “these different mechanisms result in subtle dif-

ferences in current and sediment transport patterns that are difficult to measure in the field”.

Bars have been reported to migrate at rates ranging from 8 m/yr (Gelfenbaum and Brooks, 2003) to 10–20 m/yr (Goud and Aubrey, 1985) at timescales of from one year to a few decades. Migration rates can be higher at shorter timescales (days to a month) with reported rates of 1.75 m/month (Gelfenbaum and Brooks, 2003) to 22 m/day along the Dutch coast (Ribas and Kroon, 2007), and up to 40 m/day in North Carolina (Konicki and Holman, 2000). In contrast, some systems appear to be quite immobile at timescales of years to a decade, as Niedoroda and Tanner (1970) and Bruner and Smosna (1989) have shown. Gelfenbaum and Brooks (2003) identified a bar migration direction opposite to the residual longshore sediment transport direction indicated by Davis and Barnard (2003).

The foregoing literature review suggests that transverse bars are characterised by marked variability in terms of size, potential formational mechanisms and migration rates, although they have, thus far, only been reported from low to moderate wave-energy microtidal coasts. Transverse bars have received much less attention in the literature compared to other inner shoreface bar types such as longshore and crescentic surf-zone bars and swash bars. This is surprising given the fact that transverse bars can store large quantities of sediment and can play a role in modulating nearshore wave energy, both of which are important in terms of coastal stability and management. McNinch (2004) and Schupp et al. (2006) showed, for instance, the influence of such bars on longshore patterns of shoreline change at a range of spatial and temporal scales. The aim of this paper is to doc-

ument, for the first time, the morphology and dynamics of long-crested transverse bars in a large tide-range setting, based on the analysis of recent comprehensive Lidar datasets.

2. Study area

The transverse bars reported in this study occur near a tidal inlet, Regnéville inlet, located on the west Cotentin coast in Normandy, France (Fig. 1). The west Cotentin coast forms a sandy and relatively rectilinear embayment comprising the Channel Islands, and indented by eight small inlets (locally called “havres”), the largest of which is Regnéville inlet. The shoreface is characterised by complex hydrody-

namic conditions as a result of variable bathymetry and the presence of the Channel Islands and numerous shoals and islets. The tidal wave propagating eastward from the Atlantic Ocean into the west Cotentin embayment is reflected by the north–south oriented coast, generating a standing tidal wave, especially in the south, within Mont Saint-Michel Bay (SHOM, 1953; Bonnefille, 1968; Chabert D’Hières and Le Provost, 1978). Northward, the tidal wave becomes progressive. The dominant M2 (lunar and semi-diurnal) harmonic is associated with a virtual amphidromic point located on land in south-west England north of Portland (Pingree and Griffiths, 1979). The tidal range increases sharply from the north to the south of the Cotentin coast. The exceptional spring tidal range is about 5 m in Cherbourg-Octeville but attains 15 m, one of the highest in the world, in Mont Saint-Michel Bay. The large tidal range is associated with strong tidal current activity, especially along the southern half of the west Cotentin embayment. The offshore mean currents are paral-

lel to the coast during most of the tidal cycle and can reach 1 m/s (Levoy, 1994). Maximum speeds are attained near high and low tide stages. These currents are directed northward around high tide and southward at low tide. The tidal range at Regnéville inlet is 11 m at mean spring tides and reaches 14 m during exceptional spring tides. These conditions produce, per tidal cycle, a mean tidal prism of 15.106 m3 and a mean spring tidal prism of 46.106 m3 within Regnéville lagoon. The average freshwater discharge in the lagoon represents only 0.2% of the mean spring tidal prism (107 m3).

The west Cotentin coast is exposed to local wind waves and resid-

ual swell from the North Atlantic. However, wave propagation is compi-

cated as a result of the irregular shelf bathymetry, which results in significant wave attenuation (Levoy, 1994). Further wave modifications are caused by rock platforms and intertidal ebb deltas. Recorded off-

shore wave heights at Les Nattes (Fig. 1) are less than 0.5 m 65% of the time. Wave heights exceeding 1.5 m are observed only 2% of the time. The waves come mainly from a west window (waves from south-

west to northwest (230°–310°) represent more than 90% of the obser-

vations) in response to the prevailing synoptic winds in this region. Local westerly winds are active in winter and generate waves with periods of 4–6 s. These local–fetch waves are mixed with rare North Atlantic swell with periods ranging from 8 to 12 s. The west Cotentin embayment may be viewed as a very large dissipative embayment with decreasing wave heights from north to south and from west to east.

Robin and Levoy (2005) and Robin et al. (2007, 2009a) have provid-

ed a general overview of the hydrodynamic conditions in the intertidal zone of the northern part of the ebb delta of Regnéville inlet. They
showed that significant wave heights varied markedly as a function of tide-modulated water depths. Wave heights were at a maximum at high tide and decreased with the water level, in agreement with other studies on other sandy macrotidal coasts (e.g., Russell et al., 1991; Voulgaris et al., 1996; Levoy et al., 2001; Anthony et al., 2004, 2005; Reichmüth and Anthony, 2007; Sedrati and Anthony, 2007). Mean current velocities are influenced by the neap-spring cycle and by wave energy levels (Robin et al., 2009b). During spring tides and low wave-energy conditions, mean maximum currents attain up to 0.8 m/s around high tide and are dominated by longshore flows setting northward to northwestward (306°–343°). During spring tides and stormy conditions, these longshore currents are weaker at the beginning and at the end of the tidal cycle, when cross-shore currents dominate. During neap tides and low wave conditions, mean maximum currents are generally weak (hardly exceeding 0.08 m/s), but still dominated by tide-induced longshore currents. These neap tide currents are reinforced during stormy conditions when relatively strong cross-shore currents prevail in shallow water conditions. Under these neap tide conditions, as the tidal level rises, mean cross-shore speeds decrease while longshore ones increase attaining maximum values of about 0.25 m/s at high tide, with currents setting northward.

Regnéville inlet is diverted by Agon Spit, a large and complex sand spit (Fig. 2), subject to southeastward migration, and the distal end of which currently exhibits eight recurves. These recurves are fed by wave-induced longshore transport complemented by the onshore migration of wave-formed swash bars that are quite distinct from the long-crested transverse bars described in this study. These swash bars are typical large delta shoal bars (Robin et al., 2009b). They are prominent features with a volume of about 25,000 to 30,000 m³ of sand each and crest elevations of up to 2 m, and they migrate landward over the ebb delta platform under wave influence. The onshore welding of each swash bar, over a multi-annual timescale, is responsible for the formation of each new spit recurve (Robin and Levoy, 2007; Robin et al., 2009a). The sand circulation in the high-tidal zone corresponds to the wave-generated longshore drift on this coast. This drift is only significant at high tide, when wave heights are much less attenuated as a result of the larger depths, and only during moderate to strong wave conditions (Levoy et al., 2000). The north–south wave-induced littoral drift along Agon Spit is estimated at about 40,000 m³/yr, but drift along the coast immediately south of the diverted inlet is directed northward as a result of wave refraction over the ebb delta (Levoy, 1994). This wave-induced bi-directional drift results, therefore, in sediment convergence at the ebb delta platform. The Regnéville ebb delta is large and shallow near the inlet as a result of accretion. The exposed part of this delta at low spring tide extends more than 4 km offshore. The strong tidal currents induce northward transport of sand over large areas of the shoreface in the study area. This northward sand transport runs counter to the sand drift direction in the high-tidal zone driven by waves.

3. Methods

3.1. Lidar datasets

The study area was repeatedly surveyed with an Airborne Laser Scanner (Leica ALS60) over a 2.5-year period between February 2009 and September 2011. Repetitive Lidar datasets are essential in
analysing the movements of transverse bars, but also their detailed topographic changes. The survey principle relies on distance and angle measurements between the ground and the known position and attitude of the plane. Durations of laser pulse transmission and return detected by an analogical sensor are divided by a typical light speed value adjusted after a range calibration check. The laser wavelength is 1064 nm. The laser source is a neodymium-doped yttrium aluminium garnet (Nd-YAG). It provides, at a high frequency of over 200 KHz, high-energy pulses that are trimmed with regard to the flight altitude and mean ground reflectivity (ca. 15% for sandy beaches). Easy cooling, mastered technology and the portable characteristics of the system explain the widespread use of this type of laser instrument in airborne measurements. The scanning system is an oscillating mirror, which ensures a high density of measurements as each pulse produced is transmitted to the ground. For flight altitudes greater than 1000 m above ground level (AGL) a multipulse system, consisting of the production and detection of a pair of pulses, allows for high-density measurements with a maximum coverage rate, thus reducing flight costs. Airborne Lidar systems like the ALS60 are particularly suitable for surveys of large coastal areas such as wide embayments or long corridors such as beaches (Saye et al., 2005; Shrestha et al., 2005). At present, this is the only possibility of having instantaneous characterization of large coastal zones based on accurate and dense measurements. A 22-megapixel camera can be plugged to the instrument in order to complement the detailed topographic records with very high-resolution pictures. Through this link, the accuracy of the plane position and attitude values are used for picture positioning. From the ground topography obtained from the Lidar datasets a fine distortion correction can be obtained together with coherent picture mosaics from the accurate positioning of tie points.

Records are configured with a field of view (oscillating limits of the mirror) of 40° and an average flight speed of 100 to 110 knots (<55 m/s). For every survey, two flight plans were scheduled on the basis of two AGL (above ground level) of respectively 800 m and 1500 m. The flight-plan choice is made during the flight, depending on weather conditions, and especially cloud heights, as the pulses

Fig. 2. Aerial photograph of the study area taken during the 18th April 2010 survey, showing the distal tip of Agon Spit, Regnéville inlet and locations of transverse bars. Longshore profile A-A’ is shown in Fig. 3, and cross-sections B-B’ to G-G’ are shown in Fig. 4.
cannot go through water or mistiness. Incidence angles (+/− 20° from nadir) and flight-line directions are chosen as a good compromise between object detection on the ground, accuracy needed and external flight plan constraints such as tides and cost restrictions. Flight-line sequence is adjusted during the flight with regard to the tide level, with the objective of flying over the lowest parts of the transverse bars and the ebb delta. The highest flight altitude is preferred to reduce costs but this is a compromise with a minimum density of points and accuracy. Maximum rates for pulses and mirror oscillation are considered for flight planning. The typical footprint of a point on the ground is from 19 cm (800 m AGL) to 35 cm (1500 m AGL). Details on densities and accuracy statistics (values given for one standard deviation — factory default) are shown in Table 1.

From the Lidar raw records and after trajectory post-differential DGPS computations, different system compensations need to be fixed: timing offsets, boresights, torsion, laser range calibration and fine mathematical adjustments for coherence of the overall survey. The accuracy of the system is verified by comparing independent bare ground-point measurements and the Lidar records. The results obtained during the study are better than the factory values. Furthermore, Digital Elevation Models are computed from the clouds of points. These clouds provide a mean density higher than the one given for individual flight lines, as overlaps and superposition of flight lines for calibration or other specific purposes must be taken into account. The computation of a 1-metre square gridding implies at least a minimum of 2.3 to 3.5 points per mesh size. The absolute positioning error of each point is mainly dependent on the accuracy of the trajectory. GPS errors inside a grid unit can be considered constant (order of magnitude +/− 5 cm), although the averaging of several points when calculating each grid node will reduce the error due to the scanning and laser system (order of magnitude +/− 2 cm). The spatial scale resolution will be affected but the accuracy, especially for the Z dimension, will be enhanced, partially proportional to 1/v/h.

Table 2 summarizes all the flight-line characteristics used in this study.

The bar wavelength has been defined as the average distance between two consecutive bar crests. In order to evaluate bar migration rates, the bar location for each Lidar survey was estimated from the location of the bar mass centre. To this end, 1-metre equidistant cross-sections were established and for each of these sections the location of the mass centre was computed by numerical integration using the trapezoidal method. The break in cross-section profile slope closest to the bar crest was chosen as the lateral limit for integration on the corresponding bar flank. The limit on the other flank was taken to be at the same elevation. The mass centre as an indicator of the bar location was preferred to the bar crest or one of its flanks because it is less sensitive to bar shape and its evolution in time and space, and hence is more representative of the overall movement of the bar. In order to capture bar migration rates at different timescales over the entire 2.5-year period of observation, both seasonal and annual rates were determined for each bar based on the Lidar flights dates. Seasonal bar migration rates were computed on the basis of two “winter periods”: September 2009 to April 2010, and September 2010 to April 2011 (respectively 209 and 208 days) and two “summer periods”: April 2010 to September 2010, and April 2011 to September 2011 (respectively 157 and 136 days). Two annual rates were computed: September 2009 to September 2010, and April 2010 to April 2011. Finally a two-year period, from September 2009 to September 2011, was also considered.

3.2. In situ sediment sampling and field observations

Sixteen sand samples were collected along a section parallel to the shoreline. The samples were taken at the crest of each transverse bar and in the troughs between bars at sampling distances of about 500 m. For bars 4, 5 and 6, the longest ones (Fig. 2), a second set of samples along a section located about 400 m offshore of the first one was collected from the crests of the bars. Grain-size analyses were carried out using classical sieving methods in the laboratory. Observations of bedforms on the crests of the bars and between bars were also carried out.

4. Results

4.1. Description of the bars

4.1.1. Bar morphology

Seven well-developed transverse bars are located on the north side of the ebb delta of Regnéville inlet (Figs. 2 and 3). The bar field extends approximately 1.8 km along the coast from north to south and 1.1 km in a cross-shore direction. The Lidar data also highlight the presence and progressive growth of a new bar (bar 8) close to the main inlet channel. The morphological characteristics of the bars are shown in Table 3.

The bars are located mainly in the lower part of the foreshore between about 1.5 m and −4.7 m R.A.F. 09 (French geodesic datum) and are attached to the mid-tidal zone around the mean water level (0.85 m R.A.F. 09). They start from about 150 m to 250 m from the shoreline, defined here as the contact between the dry beach sand
and the vegetated dune limit (Robin et al., 2009a). The bars have individual volumes ranging from 6,000 to 60,000 m$^3$ of sand. They are oriented obliquely to the shore, which presents two main orientations (164° and 131°, Fig. 2). The angle between bars 1 to 5 and the shore is about 65°, and for bars 6, 7 and 8, the orientations with respect to the coast are respectively 122°, 112° and 103°. For bars 7 and 8, located at the entrance to the tidal inlet, the considered orientation is that of the coast located immediately north of the inlet (131°). The angular orientation of the southernmost bars (bars 6 to 8) is hinged on that of a large groyne (108°) built in 1987 to control the migration of bars. Transverse bars are often slightly asymmetrical with steeper slopes on the downcoast flanks oriented northward, are present on the northern sides of the bars close to the plane bed area. Drainage channels are often present in the troughs between bars, but no ripples are observed in these troughs. 3D wave-generated mini-ripples or asymmetric wave ripples are also frequent (Fig. 6). More complex bedforms are also present on the crests of the bars in the northern part of the ebb delta, indicating active reworking by waves and tidal currents, with the latter being especially dominant just before tidal emersion.

4.2. Bar migration

4.2.1. Two-year and annual migration rates

The movements of five bars (1, 2, 4, 6 and 7) have been analysed. The topographic changes reveal an important northward migration of the bars (Fig. 3). The northern part of this bar subfield (bars 1, 2 and 4) migrated to the northwest by 470 m between February 2009 and September 2011. The migration rates observed between September 2009 and September 2011 vary between 1.6 m/month (bar 2) and 2.2 m/month (bar 4) (Fig. 7). The mean annual migration rates (a: April 2010 to April 2011, and b: September 2009 to September 2010) are quite similar to those over the two-year period (Fig. 7).

The mobility pattern is similar in the southern part of the bar field close to the inlet, also characterised by a net movement towards the northwest (bars 6 and 7). The mean migration rates computed between September 2009 and September 2011 are, respectively, 1.8 and 1.6 m/month (Fig. 7), also close to the values measured over a one-year period. The two-year mean rate for all the bars is about 1.9 m/month, but the bar migration rates close to the inlet are slightly lower than those on the northern margin of the ebb delta.

4.2.2. Seasonal migration rates

The migration rates over these shorter periods are different. The mean “winter” migration rate is higher than the annual and 2-year
Fig. 4. Typical cross profiles of the transverse bars, extracted from the September 1, 2011 survey. A: bar 1, profile B-B'; B: bar 1, profile C-C'; C: bar 1, profile D-D'; D: bar 4, profile E-E'; E: bar 6, profile F-F'; F: bar 7, profile G-G'; see Fig. 2 for profile locations.

Fig. 5. Typical cross-shore profile of the beach between bars 4 and 5, extracted from the September 1, 2011 survey, showing the tidal levels and tidal zones with reference to the shoreline (HAT: highest astronomical tide; MHWS: mean high water springs; MHWN: mean high water neaps; MSL: mean sea level; HTZ: high-tidal zone, MTZ: mid-tidal zone).
rates with a value of 2.2 m/month. The values are 2.3 m/month for the northern bars and 2.1 m/month for the southern bars. Bar 1 has been particularly active, with a mean displacement of 2.7 m/month between September 2009 and April 2010 and September 2010 and April 2011 (Fig. 7). The “summer rate” is lower than the winter rate with a mean value close to 1.3 m/month for the five bars. The rates are respectively 1.4 m/month for the northern bars and 1.2 m/month for the southern bars. The mean summer movement of bar 7 was about 1.4 m/month (Fig. 7), but was very variable, being relatively low at 0.4 m/month between April and September 2010 and higher at 2.4 m/month between April and September 2011. These results show that bar mobility can be quite variable over a year.

4.2.3. Migration during spring tides without wave activity

A single Lidar survey was conducted on April 14, 2010, just before the main survey of April 18. The flights covered bars 1 to 7. Topographic comparisons at this short four-day timescale (Fig. 8) enable an appreciation of the influence of forcing conditions. Mean spring-tide conditions prevailed on April 14 and the weather was calm with onshore winds (north-northeast to east) blowing at a mean speed of less than 5 km/h (the maximum speed was less than 20 km/h). Under these conditions, wave activity was negligible. On April 18, the weather was also fine with a mean onshore wind (east) of less than 8 km/h (maximum less than 17 km/h). As on April 14, no significant wave activity was observed. Exceptional spring tide conditions prevailed on April 18 during the second Lidar flight. During these spring tide conditions, no significant movement was recorded for bars 6 and 7, but bars 1, 2, 4 and 5 moved northwestward as indicated by the loci of erosion and deposition surfaces (Fig. 8). The measured movements of the bars were 2 to 4 m over a period of 4 days (0.5 to 1 m/day).

4.3. 3-D bar and ebb-delta evolution between February 2009 and April 2011

Fig. 9 depicts a complex 3D topographic evolution of Regnéville inlet between February 2009 and April 2011. Several features can be identified on this image. The northward migration of the transverse bars is clearly observed with erosion areas located just southward of accretion surfaces. The morphological changes of bar 8 derived from the Lidar data are shown in Fig. 10. This picture shows clearly the elongation of a sedimentary body that then becomes immobile (no significant alongshore migration). This bar, obliquely oriented with respect to the channel axis, also becomes narrower. The lateral migration of the main inlet channel is also obvious (Fig. 9) with erosion and accretion areas located on each bank of the channel. The image also shows the onshore migration of the swash bar between bars 5 and 6. Robin et al. (2009b) showed that such swash bar migration occurred under the action of storm waves. The migration rate of the swash bar over the 2.5 yr period is about 60 m/yr. On the upper part of the foreshore, an 800 m-long erosion swath is observed along the distal end of the sandy spit, together with a large surface of sand accumulation close to the channel (Fig. 9).

5. Discussion

The discussion will focus on the following aspects: (1) the relationship between the transverse bars and Regnéville inlet, especially in terms of sediment sourcing and bar formation, (2) the fate of the bars following their northward migration, and (3) the specificities of these long-crested macrotidal transverse bars compared to bars described in the literature from microtidal settings.

5.1. Sediment sources and processes of transverse bar formation

The remarkable proximity of the transverse bars to the Regnéville tidal inlet suggests kinship between this inlet and the presence of the bar field. Regnéville inlet is the largest of the inlets on the Cotentin coast and is, therefore, subject to a relatively important tidal prism that provides a primary functional link between sediment supply for
bar formation and the ebb tidal jet. The locus of new bar formation (bar 8) and the northward migration of the bars, normal to the shore, over seasonal, annual, and longer (2.5 yr) timescales clearly suggest that bar formation occurs close to the tidal inlet. The sediment involved in the formation of the bars is apparently primarily derived from the large ebb-tide platform, and secondarily from what appear to be small wave-formed swash bars that are further discussed below. The observations reported in the preceding section from the image in Fig. 9 show the co-existence of erosion and accumulation zones along the shore north of the inlet. The 800-m erosion swath along the shoreline releases sediments that then migrate to form a sedimentary platform close to the channel. Regnéville inlet is thus sourced in sands that circulate from northwest to southeast in the high-tidal zone, whereas the sand circulation pattern on the ebb delta, which also corresponds to that of the transverse bars, is opposite, from southeast to northwest. As the north-south longshore drift is perturbed by the large ebb-delta swash bar (see Fig. 2), the shore located downdrift of this swash bar becomes undernourished, resulting in the 800-m erosion swath of the high-tidal zone along Agon spit. This eroded sand ends up in the ebb delta at the tip of

Fig. 8. Bar topographic changes between 14th and 18th April 2010. Longshore profile H-H’ is shown in Fig. 2.
Fig. 9. Topographic changes and bar and channel dynamics in the study area between February 2009 and April 2011. TBF: transverse bar formation; TBM: transverse bar migration; SBM: swash bar migration; CM: ebb delta Channel Migration.

Fig. 10. Formation and evolution of transverse bar 8. A: 12th February 2009; B: 18th April 2010; C: 22nd September 2010; D: 18th April 2011, and E: 1st September 2011. The red arrow in C shows a small swash bar welding onto bar 8. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
the spit and then becomes available for bar development. Field observations on several occasions in the course of the 2.5-year study period also show the development of small asymmetrical sandy swash bars (mean volume of few tens to hundreds of m³), distinct from the larger ebb-delta swash bar mentioned earlier, that became incorporated into bar 8 (see annotation on Fig. 10). These observations show clearly a complex sourcing system from the ebb-delta platform, the primary source, and small wave-formed bars.

Mechanisms proposed for transverse bar formation are generally based on surf-zone processes and self-organisation under conditions of significant wave activity (e.g., Garnier et al., 2006; Ribas et al., 2011, 2012). The mechanisms involved in the formation of the transverse bars of Normandy will need more detailed field hydrodynamic and modelling studies, but they do not seem to be simply related to the same processes invoked for bars in microtidal settings because of the overarching effect of tidal currents. The mechanism of formation most likely resides in interactions, at Regnéville inlet, involving the tidal inlet ebb jet, the strong shore-parallel tidal currents setting to the northwest, and refracted waves from the west and northwest. The outflowing ebb jet is deflected WNW by the longshore tidal currents. This jet is likely to be further channelised by the 1987 groyne (Fig. 2). Once formed, the migration of the bars away from the inlet zone is assured by the strong spring tidal currents, as shown by the April 2010 Lidar experiment during which waves were low. Migration rates during spring tides are enhanced by wave resuspension of sand during storms, as shown by the larger “winter” migration rates compared to the “summer” rates. It must be noted that mobility during the brief April 2010 experiment concerned only bars in the northern part of the bar field (bars 1, 2, 4, 5), where spring tidal currents setting to the north were probably strong and unimpeded. Bars 6 to 8, close to the inlet, remained immobile over the same period, under the control of the deflected inlet ebb jet. The strength of this ebb jet may thus explain why bars 6 to 8 migrate at lower rates than the bars further north (bars 1 to 5). A probable result of the strong ebb flow is that it refracts and weakens the shore-parallel spring tidal currents that drive active bar migration northwards.

Bars are also reworked by storm waves as the tide falls. The bars are successively under the influence of shoaling waves, breaking waves, and swash. Reworking of the surface of the bars on the northern wave-exposed flank of the ebb delta and near the shoreline by such wave activity induces, for instance, temporary asymmetry towards the south, notwithstanding overall migration towards the north.

5.2. The fate of the bars

The bars are generated exclusively in the vicinity of Regnéville inlet and progressively migrate northwards away from the inlet, disappearing over time in the northern part of the study area. At the same time, the inlet is subject to slow multidecadal-scale southward migration as lengthening of the distal tip of the Agon Spit occurs under southward-directed longshore drift. As the transverse bars migrate northward away from the inlet, and towards the more wave-exposed sector of the western Cotentin coast, they are probably integrated into the large dissipative Cotentin embayment, which has been shown to act as a source of sand for the development of aeolian dunes on the Normandy coast (Anthony, 2004), and which is characterised by a number of large-scale tidal gyres related to the intricate bathymetry of islands, shoals and islets (Garnaud et al., 2000), as well as by smaller observed local gyres close to the shoreline. Sand recycled by storm waves from these aeolian dunes appears to source the longshore drift to the south that contributes to the sand supply involved in transverse bar formation. The transverse bars thus appear to be part of a large-scale, long-term sand recycling process between Regnéville inlet and the central part of the Cotentin embayment.

5.3. Comparisons with transverse bars in microtidal settings

Table 4 is a synthesis of the hydrodynamic conditions and morphology of transverse bars described in the literature, compared to the bar field in Normandy. The transverse bars described in this study fall in the class of the long-crested bars. A common feature of transverse bars in this literature review is their low to moderate wave-energy setting and the commonality of low tidal range conditions. The main differentiating factor of the Normandy bars concerns the large tidal-range setting, which also sets the template for the processes of bar formation and migration, and conditions variability in bar morphology. The strong tidal currents, absent in microtidal settings, constitute the dominant forcing factor in transverse bar migration, whereas variability in bar morphology in space and time is conditioned by the large tidal range and by tidal modulation of waves and currents. Such strong tidal currents thus play a role that is equivalent to that of wave-induced longshore currents generally correlated with the migration of transverse bars in open-coast settings (Ribas et al., 2012).

Bar migration rates are no doubt determined by fine balances hinged on bar volume, exposure to wave energy and duration of tidal current activity. The migration rates of the Cotentin bars are about 20–25 m a year, and migration occurs over periods of several years. At a shorter timescale, during spring tides without wave activity, the migration rates are about 0.5 to 1 m/day. These rates are slower than those of small-crested, and rather ephemeral, open-coast bars such as those of the US Virginia and North Carolina coasts and the Netherlands, but are comparable to those observed for the long-crested transverse bars of the Florida and Massachusetts coasts (Table 4) where wave energy is lower than on the Normandy coast but where the low tidal range allows for longer durations of wave reworking. The largely subtidal volume of transverse bars in microtidal settings renders them durably exposed to wave processes and longshore currents during storm events. The relatively low migration rates on the macrotidal Normandy coast are explained by the long period of emergence of the intertidal zone during each semi-diurnal tidal cycle, which reduces the duration of efficient tidal current and wave action on the large transverse bars. The role of wave action in enhancing these rates will need to be monitored during stormy conditions. Finally, the large tidal range also generates variability in migration rates in the course of the neap-spring tidal cycle.

The macrotidal transverse bars of Normandy also appear to be inscribed in a sand recycling system. Their initial sand sourcing is from wave-induced shoreline and beach erosion that releases sand transported southward by longshore drift towards the macrotidal Regnéville inlet where ebb tidal accumulation provides a source for the formation of the bars. The link between the transverse bars of the Normandy coast and a tidal inlet is a common feature of transverse bars, as noted, for instance, by Gelfenbaum and Brooks (2003). This link is probably related to the important accumulation of sand in the vicinity of tidal inlets and its availability for transverse bar formation.

6. Conclusions

1. Transverse bars have been generally reported from microtidal coasts. This study describes, for the first time, intertidal transverse bars from a macrotidal coast. The overarching difference between the long-crested transverse bars of Normandy and transverse bars described in the literature resides in the large tidal range setting (mean spring tidal range of 7 to 12 m on the west coast of Cotentin), which conditions bar formational mechanisms, morphological variability and migration rates.

2. The formation of these bars seems to be directly related to the presence of a tidal inlet characterised by an ebb tidal jet deflected northward by the strong shore-parallel tidal currents prevailing on the west-facing coast of Normandy. The ebb delta serves also as a sand depocentre from which the transverse bars are formed. The mechanism of formation of the bars most likely resides in interactions.
Table 4
A literature summary of hydrodynamic conditions and morphology of transverse bars compared with the bars in Normandy.

<table>
<thead>
<tr>
<th>Reference</th>
<th>General context</th>
<th>Tidal conditions</th>
<th>Wave exposure</th>
<th>Bar wavelength</th>
<th>Cross-shore length</th>
<th>Bar height</th>
<th>Longshore migration rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carter (1978), Ireland</td>
<td>Lake Embayment on the backshore of a major barrier island</td>
<td>Tidless</td>
<td>Breaker height less than 0.1 m</td>
<td>5–6 m</td>
<td>1–13 m</td>
<td>0.1 m</td>
<td>2–3 m/d (landward migration)</td>
</tr>
<tr>
<td>Bruner and Smosna (1989), Virginia</td>
<td>Large man-made lake, associated with shore-parallel bedforms</td>
<td>Mean tidal range: 0.4 m</td>
<td>Storm conditions: wave heights up to 1.4 m</td>
<td>About 20–30 m</td>
<td>45–70 m</td>
<td>No data</td>
<td>Slow migration, rate not given</td>
</tr>
<tr>
<td>Khabidov (2001), Russia</td>
<td>Estuarine environment</td>
<td>Mean tidal range: 0.7 m</td>
<td>Mean breaker height: 0.06 m 64–218 m</td>
<td>40–80 m</td>
<td>50–200 m</td>
<td>0.2 m P</td>
<td>Slow migration, rate not given</td>
</tr>
<tr>
<td>Eliot et al. (2006), Western Australia</td>
<td>Low energy coast, Gulf of Mexico</td>
<td>Mean annual ( H_{av} ): 0.19 m</td>
<td>Storm wave conditions: 1–1.3 m</td>
<td>About 150–300 m</td>
<td>About 300–1500 m</td>
<td>0.5–0.6 m P</td>
<td>No data</td>
</tr>
<tr>
<td>Niederoda and Tanner (1970), Florida</td>
<td>Protected from open ocean swell Nantucket Sound</td>
<td>Mean annual wave height: 0.25 m</td>
<td>No information on waves. Fetch of 4 km</td>
<td>20–270 m</td>
<td>80–100 m</td>
<td>0.5 m P</td>
<td>No data</td>
</tr>
<tr>
<td>Goud and Aubrey (1985), Massachusetts</td>
<td>Low energy coast, Gulf of Mexico</td>
<td>Mean annual ( H_{av} ): 0.06 m 64–218 m</td>
<td>No information on waves. Fetch of 4 km</td>
<td>107–640 m</td>
<td>50–200 m</td>
<td>0.2 m P</td>
<td>No data</td>
</tr>
<tr>
<td>Gelfenbaum and Brooks (1998, 2003), Florida</td>
<td>Protected from swell; Bay of Santander</td>
<td>Mean tidal range: 0.7 m</td>
<td>No information on waves. Fetch of 4 km</td>
<td>25 m</td>
<td>21–75 m</td>
<td>0.5 m P</td>
<td>No data</td>
</tr>
<tr>
<td>Garnier et al. (2012), Bay of Santander, Spain</td>
<td>Open coast, subtidal and ephemeral transverse bars existing with longshore bars and troughs</td>
<td>Mean tidal range: low mesotidal</td>
<td>No information on waves. Fetch of 4 km</td>
<td>25–100 m</td>
<td>15–60 m</td>
<td>0.5–2.5 m P</td>
<td>No data</td>
</tr>
<tr>
<td>Konicki and Holman (1996, 2000), North Carolina</td>
<td>Open coast, subtidal and ephemeral transverse bars existing with longshore bars and troughs</td>
<td>Mean tidal range: 0.97 m</td>
<td>No information on waves. Fetch of 4 km</td>
<td>1.9 m/month over 2 yr. 0.5 to 1 m/day during spring tides</td>
<td>Mean tidal range: 1.6 m</td>
<td>8.3 m</td>
<td>Mean tidal range: 1.6 m</td>
</tr>
<tr>
<td>Ribas and Kroon (2007), Dutch Coast</td>
<td>Exclusively intertidal, on the surface of a macrotidal ebb delta shoal</td>
<td>Mean tidal range: 107–640 m</td>
<td>No information on waves. Fetch of 4 km</td>
<td>0.9 m</td>
<td>Mean tidal range: 0.8 m</td>
<td>Mean annual Hs: 0.46 m (at a mean water depth of 12.4 m)</td>
<td>Mean annual ( H_{av} ): 0.8 m</td>
</tr>
<tr>
<td>Cotentin coast, Normandy, France (this study)</td>
<td>Exclusive intertidal, on the surface of a macrotidal ebb delta shoal</td>
<td>Mean tidal range: 8.3 m</td>
<td>Mean annual Hs: 0.46 m (at a mean water depth of 12.4 m)</td>
<td>107–640 m</td>
<td>107–640 m</td>
<td>0.5–2.5 m P</td>
<td>Mean annual Hs: 0.46 m (at a mean water depth of 12.4 m)</td>
</tr>
</tbody>
</table>

Bar height Persistent (P)/transient (T)

Alongshore migration rate 2–3 m/d (landward migration)
involving the tidal inlet ebb jet, the strong tidal currents, and refracted waves from the west and northwest. Elucidating the mechanisms of bar formation will need more detailed field hydrodynamic and modelling studies in the future, in addition to Lidar monitoring at different timescales.

3. The transverse bars in this large tidal range setting are subject to migration towards the north, under the influence of the strong shore-parallel spring tidal currents that flow northwards during a large part of the tidal cycle. Migration during spring tides may be enhanced by storm wave resuspension of sand. This migration direction is opposite to that of wave-induced longshore drift on this coast, which feeds the distal elongation of Agon Spit near the ebb delta, via the shore attachment of wave-formed swash bars. This longshore drift also sources the ebb delta in sand involved in transverse bar formation. The overall pattern suggests a coastal sand recirculation cell similar to those reported for transverse bars in certain microtidal settings.

4. Transverse bar migration rates in this macrotidal setting attain up to 25 m/yr. Migration rates are lower in the vicinity of the tidal inlet where the bars are formed, but increase further north away from the inlet. This rate variability is probably related to an along-shore gradient in the strength of tidal currents, which are modified over the hydrodynamically complex shallow ebb delta platform, but are unimpeded and shore-parallel north of the inlet. Bar migration rates are also dependent on the semi-diurnal tidal cycle in the large tidal range setting of Normandy, and are further modulated by the neap-spring tidal cycle, as well as by seasonal variations in wave conditions, being higher in winter than in summer.

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