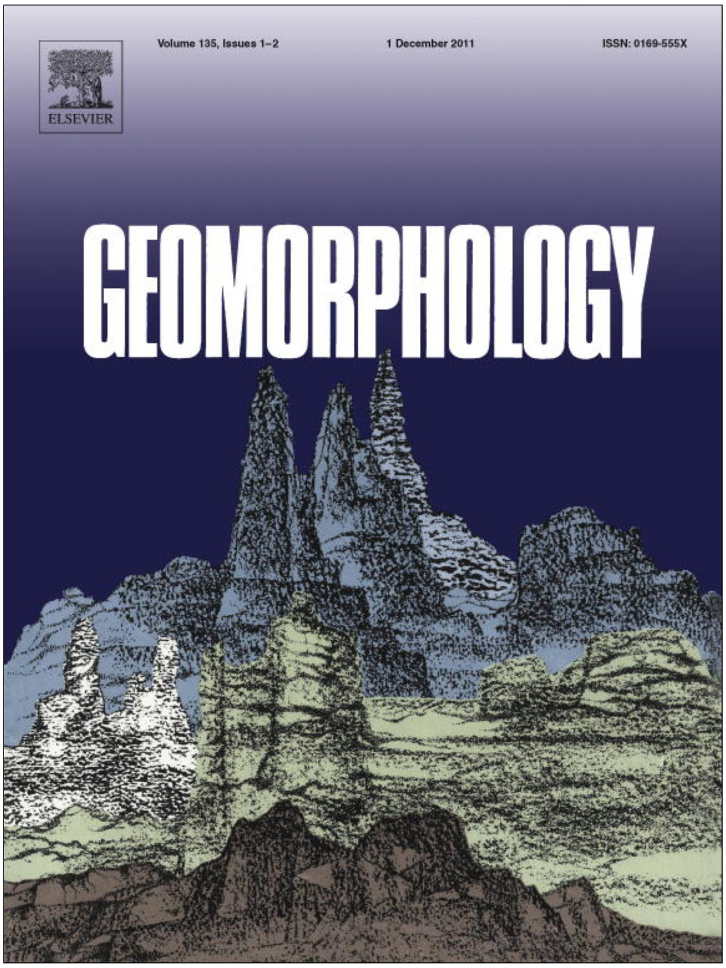
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Morphodynamic characteristics in a tidal inlet: San Blas, Argentina

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ABSTRACT

A tidal inlet on the Argentinean coast is studied. An integrated approach of combining detailed bathymetry survey, seabed sampling and tidal current measurements was used to characterize the tidal inlet morphodynamics. A Phase Measuring Bathymetric System (PMBS) "GeoSwath Plus" from GeoAcoustics Ltd. with centimetric precision and a mean swath coverage of 160 m, was used to recognize bedform morphologies and to determine bedform dynamics by comparison of successive surveys . Tidal velocities were recorded during a complete tidal cycle using an ADCP mounted on a ship operating at a frequency of 650 kHz. Maximum tidal currents, of the order of 2 m s^{-1}, exhibit different patterns across the channel. While maximum ebb currents dominate in the central and southern area of the channel, flood maximum currents dominate on the northern flank. The complex morphology of a dune field in an inlet and the resulting 3-D dune movement mechanism are also presented. In the middle of San Blas channel, a field with symmetrical large dunes (10–100 m in spacing) and very large dunes (>100 m in spacing) 4.5 to 5 m in height was found. Dune migration rates were measured by comparing two successive morphological maps of the field, reaching a rate up to 21 m year^{-1} toward the ocean. In contrast, the smaller dunes present on the northern border of the field migrate in an inward direction at a rate of 15.7 m year^{-1}.

1. Introduction

The classic definition of a coastal inlet is a narrow waterway connecting a bay, lagoon or similar body of water with the ocean (Fitzgerald, 1996), in which the tide ebbs and flows. In addition to the interlink between the adjacent coast and the tidal basin area, tidal inlets play an important role in coastal ocean processes as they provide the link between the coastal oceans and the protected tidal embayments, exchanging fresh and saline water, coarse and fine sediments, nutrients, planktonic organisms and pollutants between them.

The tidal movement through an inlet is constrained by the geometry of the channel and the bay in simple analogy to water flowing through a pipe, where tidal currents are accelerated. These tides entering the bay (flood) or exiting the bay (ebb) may produce water velocities sufficient to transport sand. The source of the sand is a combination of littoral drift material carried into the general area by waves, the sediment scoured locally from the channel bottoms and sides themselves and the sediment transported by rivers from land. Because the water velocities vary considerably in strength over a single tidal cycle and over longer periods, the sand entrained in the flows may be deposited, resuspended and re-deposited in a continuous process forming complex bedform patterns (e.g. Hayes, 1975, 1979; Oertel, 1975; Hubbard et al., 1979; FitzGerald, 1988; Kana et al., 1999).

Sediment transport, sediment budgets and resulting morphological evolution of tidal inlets have already been widely studied by coastal engineers and sedimentologists (Oertel, 1972, 1975; Dean and Walton, 1975; Hayes, 1980; Fitzgerald, 1996; Komar, 1996; Balouin et al., 2001; Bertin et al., 2005). While the majority of the inlet openings mentioned in the literature are known to be the result of storm breaching by marine processes, the inlet studied here has a location and a historical persistence suggesting it is linked to underlying geologic conditions (Ambrosini, 1984).

The study area is Anegada Bay, the coastal zone of the southern part of Buenos Aires Province (Argentina) where there are presently three tidal inlets exchanging water. The southern one, San Blas channel, is the deepest one and may be an example of a tidally dominated inlet.

In the present study, an integrated approach of combining detailed bathymetry survey, seabed sampling and tidal currents measurements was used to characterize the tidal inlet morphodynamics. Among others, Todd (2005) affirms that a new generation of three-dimensional sedimentary bedform mapping has arrived with the advent of multibeam sonar over the last decade. This new technology has revolutionized sea floor mapping, providing 100% coverage with unparalleled resolution, and reveals previously unrecognized bedform morphologies and sediment attributes (e.g. Courtney and Shaw, 2000). For the present

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study, a Phase Measuring Bathymetric System (PMBS) "GeoSwath Plus" from GeoAcoustics Ltd., UK was used. This system works in a similar manner as multibeam sonars, but with only a pair of transducers and measuring the phase difference of the backscattered acoustic signals in order to compute distances and angles to determine lateral positions and depths. With the resolution of the PMBS (less than 1 cm) together with RTK DGPS (accuracy less than 1 m) it is now possible to map dune locations and to trace their evolution with sub-metric accuracy.

Many of the relationships developed between dunes and their controlling environmental variables have been established in laboratory flumes with unidirectional, steady, uniform currents (e.g. Maddux, et al., 2003; Venditti, 2003; Best, 2005), which are conditions that rarely apply to dunes in natural settings. This is particularly true in estuaries where dunes are affected by temporal and spatial variabilities in flow resulting from changing fluvial and tidal conditions (Kostaschuk and Best, 2005). Also, there is a significant gap in the understanding of flow over fully 3-D dunes, and there is a pressing need for studies and measurements over three-dimensional dunefields linked to detailed laboratory studies (Parsons, et al., 2005; Best, 2005). Stolk (2000) believed that the data and studies on dunes were, and still remain, too scarce for realistic modeling.

Taking into account that in the last years the methods to constrain the position of sedimentary structures has improved and are sufficiently precise, data on dune migration are important for model validation and improvement. So, in this work the complex morphology of a dune field in an inlet and the resulting 3-D dune movement mechanism are presented. It is expected that these field results can be used to enhance laboratory investigations and thus to improve appropriate sediment transport and morphodynamic models.

1.1. Regional setting

Anegada Bay is a shallow area with depths usually less than 5 m, separated from the Atlantic Ocean by several islands. This area is connected to the ocean waters by three main tidal inlets, called from north to south Oruga, Culebra and San Blas channels, with maximum depths from 15 to 28 m. San Blas channel, 2.5 km wide and 12 km in length, is the deepest tidal inlet of the area (28 m). The town of Bahía San Blas is located on the southern margin of this channel (Fig. 1).

The tide is classified as mixed, mostly semi-diurnal. In terms of tidal range, the Bahía San Blas area is characterized as meso-tidal. The mean and maximum tidal range are 1.62 m and 2.5 m, respectively. The reversing tidal currents are the most remarkable motion of flows in the tidal inlet. Based on statistical analysis over measurements made on 2008, the mean wind speed is normally between 15 and 40 km/h, with the more frequent winds coming from the north and the faster ones from a NNE direction (Beigt, personal communication).

Few studies have been conducted in the area. Most of them involved the geomorphology of the littoral zone, with emphasis on the characteristic gravel ridges present here (Trebino, 1987; Weiler, 1996). Alvarez and Rios (1988) did the only oceanographic research carried out in the area, performing the first general bathymetry and current measurements of some specific sites within the channel.

The geology of the zone is made up of a Tertiary unit and a Quaternary sedimentary cover where marine and continental deposits can be morphologically recognized (Trebino, 1987). Ambrosini (1984) proposed a model of evolution that considers a strong littoral drift to the north, shaping the form of Jabalí Is. The longshore sediment transport developed coastal barriers formed by gravels and spits that were eroded by changes in wave climate energy.

Remarkable morphological and textural differences occur along the coast of the area. Close to the mouth (A in Fig. 1), a dissipative beach with medium sand and a gentle slope is present. Near the central part (B in Fig. 1), the beach is steeper, reflective beach profile formed by gravels. Toward the north, in the inner part of Anegada Bay (C in Fig. 1), wave cut platforms and marshes covered with *Spartina alterniflora* are present, yielding the most conspicuous characteristics of the coast.

2. Methods

A detailed bathymetric survey was conducted over a zone of 50 km^2, covering the San Blas channel, by means of a digital echosounder Bathy-500 MF positioned by DGPS operating in real time. Fifteen transversal and three longitudinal tracks were carried out in order to get the necessary bathymetric information to build the bathymetric chart of the area. Depth data were collected between October 22 and 26, 2007.

Over a zone of 3.5 km^2 characterized by a field of subaqueous dunes, a Phase Measuring Bathymetric System (PMBS) called Swath Bathymetry System "GeoSwath Plus" from GeoAcoustics Lt. (UK) was employed in October, 2008 in order to determine detailed dune morphology, yielding bedform heights present on the channel bed with centimetric precision. This modern bathymetric system offers

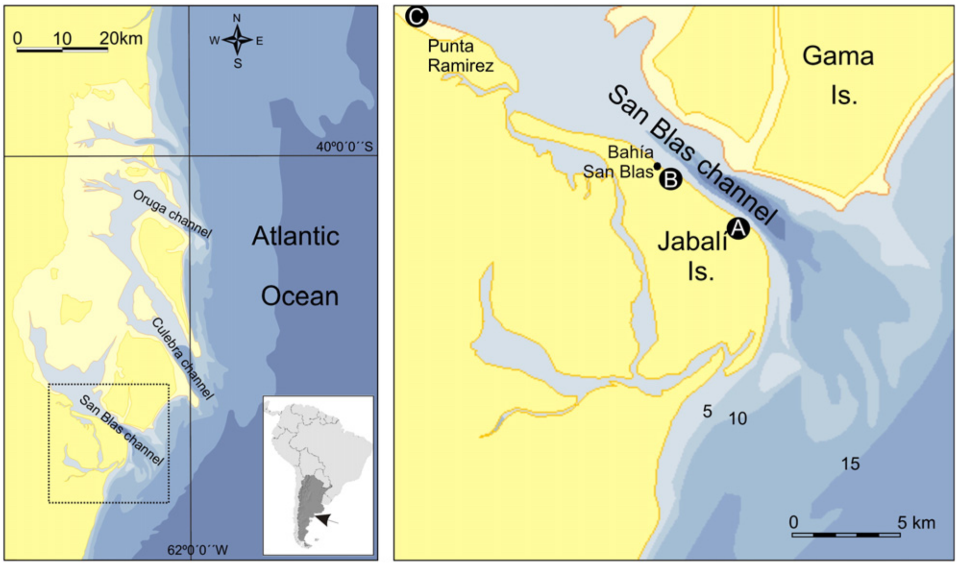

Fig. 1. Location of study area within Anegada Bay. San Blas inlet is delineated by the box. Depths are in meters.

wide swath coverage around 8 times the water depth to a maximum width of 600 m. Cross-track resolution is 1.5 cm. Although the along-track resolution depends on the rate of the swath and the vessel speed, in this research it was always less than 1 m. The system is composed of one pair of 250 kHz transducers (suitable for up to 100 m water depth), a Meridian Gyro Compass to provide heading data, a TSS DMS2-05 Motion Reference Unit (MRU) for measuring heave, pitch and roll, a surface sound velocity gauge and a mini echosounder. By means of a MIDAS sound velocity profiler (SVP) from Valeport Ltd, sound velocity was measured periodically during the survey and applied to the data to prevent sound refraction errors.

Bathymetric lines were made along a general direction parallel to the channel axis (SE–NW) with a lateral overlap in order of 50%. Eight tracks, 4 km in length covering 900 m width, were made. The bathymetric information was processed to obtain a 1-m grid spacing for the bathymetric map, where profiles and all the parameters to characterize dunes (height, H; spacing, S; depth, d) were measured with submeter accuracy. The depth data were inspected and erroneous values removed using the system's software (GS+ v 3.10). In order to determine dune migration rates, the PMBS survey was repeated nine months later, the crest positions in both maps were compared, and the distance of crest displacement measured to calculate dune migration rates (distance per year). Due to their great dimension and particular shape, each large and very large crest dunes is clearly identified through successive surveys.

On 13th March, 2008, during spring tide, tidal currents were measured continuously over a 13-h tidal cycle. Current velocity profiles were continuously recorded along a transversal channel survey line by means of a BroadBand™ (RDI) Acoustic Doppler Current Profiler (ADCP) mounted on a ship operating at a frequency of 650 kHz and being interfaced with a differential GPS navigation system. The vertical resolution was set at 0.5 m. A total of 56 transects were measured along the survey line between 0745 local time (LT) and 2100 LT. The ADCP offers many advantages over traditional measurements of velocity because it is a single, non-intrusive instrument that can be used for flow measurements (Kostaschuk et al., 2005). The current magnitudes were computed with the associated WinRiver™ (RDI) software package.

Bed surface materials were collected with a modified Van Veen grab, which sampled the upper 5–15 cm of bed material. The sample

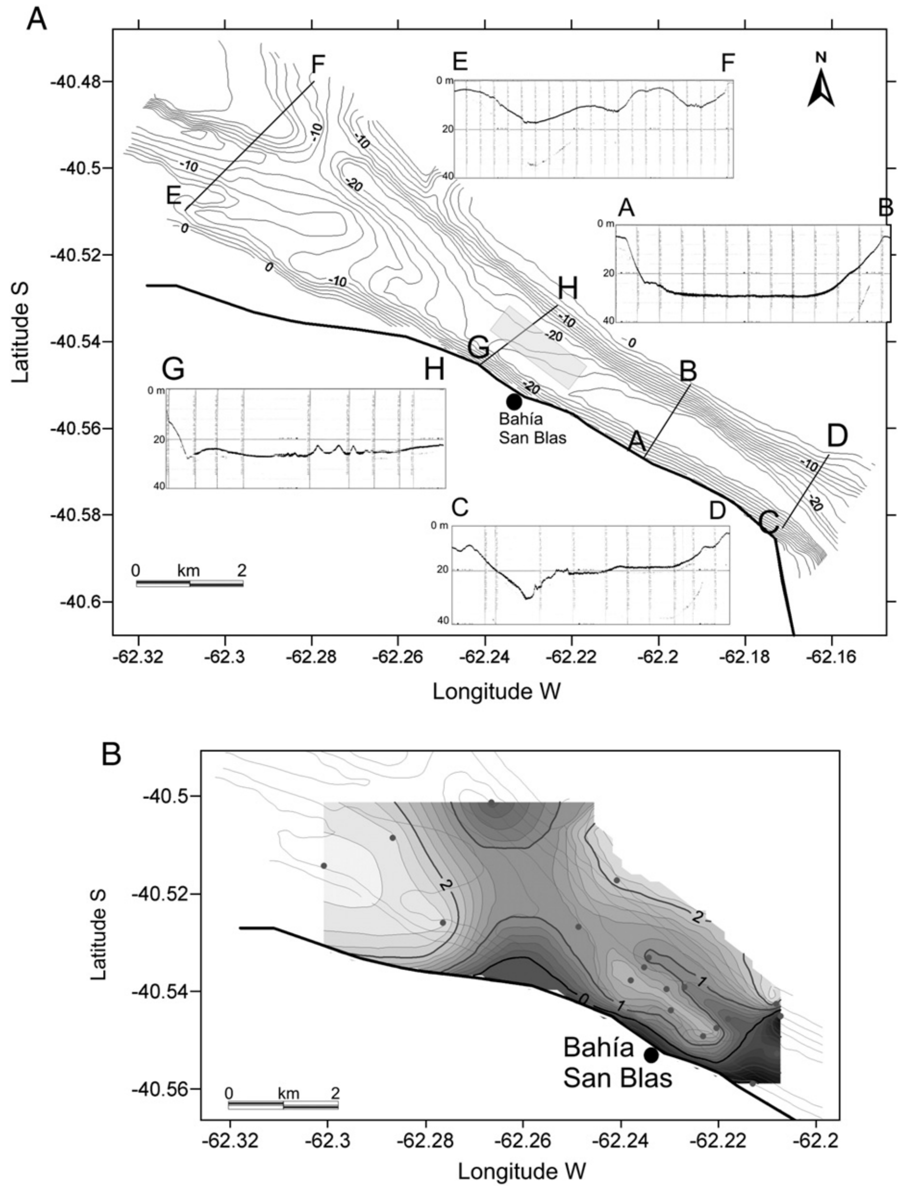

Fig. 2. (A) Bathymetric map showing profiles across San Blas inlet. The equidistance is 2 m. The shaded area indicates the dune field. (B) Bottom sediment size and sample locations. The grain size is given in phi.

positions were determined by the high-resolution navigation systems mentioned above. After washing through a 0.063-mm sieve, the samples were dried and sieved at 1/4-phi intervals. Textural parameters were calculated based on the percentile statistics described in Folk and Ward (1957).

The entire fieldwork (bathymetry, sampling, PMBS and ADCP) was performed using the 6.5 m-long boat IADO IV that belongs to the Instituto Argentino de Oceanografia (IADO). During PMBS and ADCP surveys, the boat was positioned by means of a DGPS Sokkia Radian IS operating in RTK mode, which leads to positioning uncertainties of just a few centimeters. All bathymetric data were corrected to a datum plane employing tidal records from a tidal gauge installed in San Blas town.

3. Results

3.1. Bathymetry and sedimentology

The bathymetric chart (Fig. 2A) shows different morphologies along the San Blas channel. Taking a reference line between Bahía San Blas and the opposite coast, different characteristics were found. Steep flanks to the mainland and more gentle steepness to the island is present. Inwards, depths are shallower than 20 m and, in contrast, towards the mouth an extended flat bottom of 28 m depth and 700 m width along 4 km is present (profile A–B). The flat bottom is lacking unconsolidated sediment and both flanks show a steep gradient of 3%. The southern flank maintains this slope along the coast and, in contrast, the northern flank changes to a gentler slope of 1.8% towards the mouth. Thus, a deep and narrow channel of 28 m depth is located towards the southern flank at the mouth (profile C–D). In the ocean domain, shallow submerged banks (4 m depth) build up an ebb tidal delta, which extends 7 km offshore (see Fig. 1). Wind waves bend these banks southward (Cuadrado and Gómez, 2010).

Inward along Bahia Anegada, the depth diminishes up to 15 m (profile E–F). Here there are shallow longitudinal sand bars that are exposed during low tides, and that can be seen on satellite images. Moreover, the littoral sediment transport has built a sand spit (not shown in the bathymetric chart) connected to the shore at Punta Ramirez, suggesting the occurrence of a net longshore transport close to the southern coast, toward the mouth. In the central part of the channel, a subaqueous dune field was found (profile G–H) covering a surface of 3.2 km^2, which is the focus of a more detailed analysis.

The sedimentology of the zone (Fig. 2B) shows that the most part of the channel was covered by coarse to medium sand (from 0 to 2 phi). Finer sediment (fine sand, >2 phi) was only found along the northern coast, on the flanks of Gama Island, and towards the inner bay at depths less than 10 m. This sediment builds up the sand spit mentioned previously. The coarsest sediment of the area (very coarse sand, <0 phi) was found towards the mouth of the channel, where depths are greater than 22 m; and also along the southern coast from Bahía San Blas where the sediment on the steep slope is characterized by gravels.

3.2. Hydrodynamic conditions

Fig. 3 illustrates the maximum flow structure across the channel (from Bahía San Blas to the opposite coast) for one of the full-length transects during flood and ebb currents, respectively. The results obtained from the current measurements carried out over a complete tidal cycle showed a slight difference on measured maximum velocities, as they reached 2 m s^{-1} during flood and 1.8 m s^{-1} during ebb. In addition, there was a spatial difference of the tidal currents between both tidal stages. The maximum ebb currents were found on the deepest site of the profile, in the middle of the channel and in close proximity to the southern flank, while maximum flood currents were attained mainly on the shallower zone of the channel (<24 m), from the middle to the northern flank, reaching almost to the bottom.

3.3. Dune field

The high-resolution equipment used to map the dune field (see shaded area in Fig. 2A) permits the construction of the bathymetric map gridded at a horizontal resolution of 1 m (Fig. 4A). Flow depth increases towards the SSW corner of the survey area, with a corresponding increase in dune size and spacing. On the northern edge of the field, dunes at 21 m depth have a spacing between 40 and 80 m and heights of 2.5 m. Higher dunes occur in deeper zones, at around 24 m depth, reaching heights of 4.5–5 m and spacings of about 150 m. Dunes located on the northern edge were categorized as large dunes (10–100 m spacing) in terms of the classification scheme given by Ashley (1990), while the southern ones were classified as very large dunes (spacing >100 m) (Fig. 4A). The ripple index (RI = wavelength/height) become greater towards the inlet mouth due to a rise in the wavelength (heights remain constant).

Overall, dunes have a relatively complex 3-D pattern throughout the surveyed area. They have clearly identifiable crest lines in planform, many of which are laterally continuous throughout the 800 m width of the survey area, being smaller towards the northern edge where

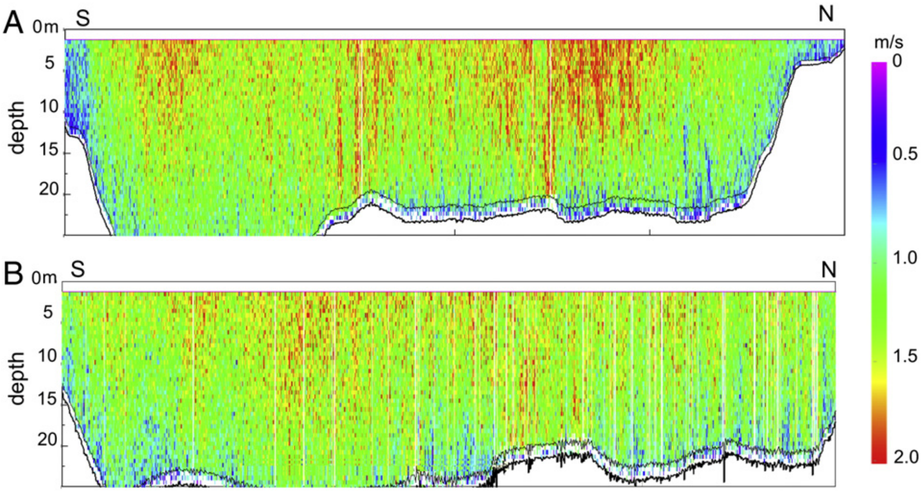

Fig. 3. Maximum tidal currents in a profile across San Blas channel from Bahía San Blas to the opposite coast showing. S: southern coast. N: northern coast. (A) Flood tide. (B) Ebb tide.

they eventually disappear. However, there are some discontinuous crest lines in-between the more continuous crest lines, frequently resulting in the confluence and bifurcation of individual crest lines. Most crest line planforms also have zones of pronounced curvature.

Most of the dunes located on the southern portion of the dune field, exhibit a symmetrical cross-section (see profile in Fig. 4). On the other hand, some dunes located on the northern side of the field are asymmetrical, with the lee side directed towards the inner part of the channel. As in tide-dominated estuaries, the superposition of smaller dunes (0.5–1 m height) on both stoss and lee sides of the larger ones is common (Gómez et al., 2010). However, it is important to note that some of the smaller dunes, mostly 2-D dunes, disappear on the crest of the larger ones.

The crest lines for the dunes located at the southern border of the field, change their direction with respect to the channel orientation from 47° to 74° towards the mouth (Fig. 4B). On other hand, the large dune crests on the northern border of the field form an angle of approximately 88° with the channel axis. In addition, the majority of the crest lines of small 2-D dunes (<1 m height) coating the field, form an angle of 95° with the channel orientation. However, the small dunes that occur in the sinus of the very large dunes present a greater angle with the channel orientation. Fig. 5 shows in detail the morphology of an area of the dune field, highlighting the smaller dunes among the larger ones. Where the spacing between the greater dunes is less than 80 m, the small dunes (15 to 40 cm in height and 5–8 m in spacing) show a rotation of the crest line to 105–107° wirh respect to the channel direction (e and d in Fig. 5). All small dunes not confined between larger ones, or where the large dune spacing is greater than 80 m, have the same crest line direction, from 91 to 94° (Table 1).

3.4. Bedform migration rate

In order to obtain bedform migration rate, a second PMBS survey was performed nine months later (Fig. 6) covering a greater area (4.5 km^2). Dunes on two consecutive maps are easy correlated due to both the high quality and the irregularity of the dune field examined.

To assure the confidence in the methodology employed in measuring dune movement, two control tracks were compared where either no bedforms were present or at least there was a very thin layer of unconsolidated sediment over bedrock (tracks a and b in Fig. 6a, b). The almost total coincidence among bed irregularities on both tracks indicates there are no errors that can be attributed to mistakes in measurements on dune position and height. The larger dunes of the area were clearly and easily identified in both bathymetric maps (as they show almost the same general shape in both surveys) but they are displaced, as can be seen in the comparative profiles (Fig. 6c). The

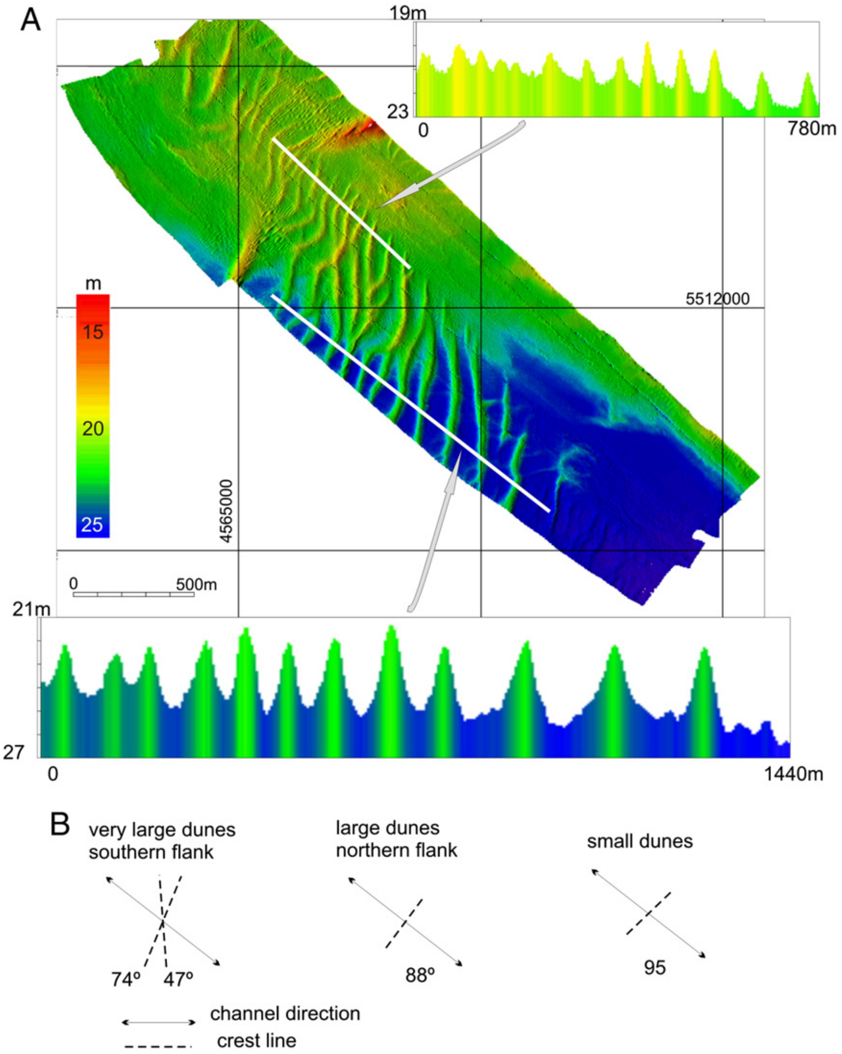

Fig. 4. (A) Morphological dune map showing different topographic profiles and their location. Coordinates are in Gauss Krüger projection (similar to UTM). (B) Crest line direction of dunes respect to the channel.

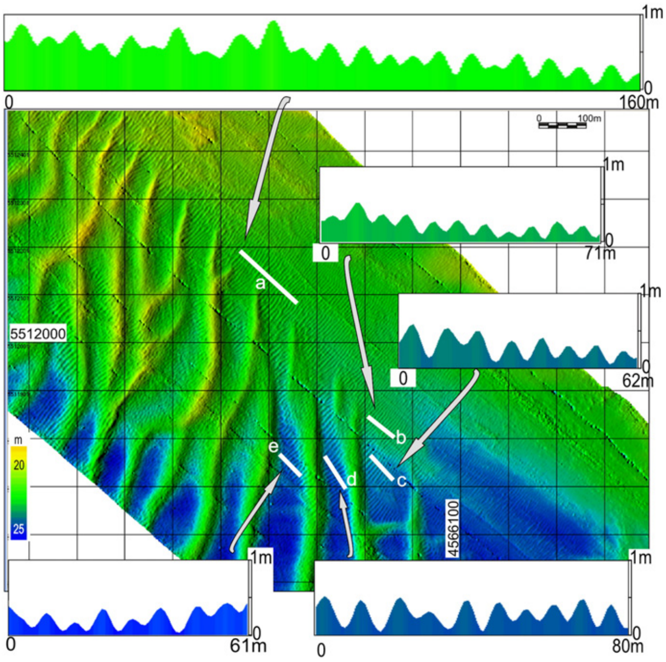

Fig. 5. Close up of Fig. 4 showing the crest orientation and profiles of small dunes.

displacement of each particular dune was computed by comparing its position in both surveys along the direction of migration (profiles A–B, C–D, E–F in Fig. 6). In Fig. 6C (profile E–F) it can be seen that the movement of dunes is greater for smaller ones.

The entire dune field shows different direction of migration, as was revealed by three profiles shown in Fig. 6. On the northern edge of the zone (profile A–B in Fig. 6C) the migration of asymmetrical dunes is toward the inner zone, with a mean displacement of 11.8 m (minimum = 6 m, maximum = 19 m, n = 11, see Table 2). In contrast, in the middle of the field (profile C–D) symmetrical dunes move towards the mouth of the channel with a mean displacement of 16.3 m (minimum = 10 m, maximum = 24 m, n = 9). The greater displacements were measured on the south–west border of the field (profile E–F), with mean values of 19.9 m (minimum = 9 m, maximum = 40 m, n = 11) where the very large dunes are present. Using the software GS+, a comparison of the dune field between both bathymetric surveys was done by subtracting both 1-m side grids. Thus, the differential displacement over each crest line is shown in detail (Fig. 7). It is clear that the migration is mostly toward the mouth (white arrows, Fig. 7B), but there is also a strip on the northern border of the dune field where migration is inwards, towards the bay (colored arrows). In addition, the point with no movement over the crest can be recognized.

4. Discussion

San Blas inlet shows a narrow strait, 2.5 km in width, between the mainland and Gama Is., connecting the south of Anegada Bay with the open sea. It exhibits typical features: a flood tidal delta in the internal zone of the bay with depths less than 15 m; an ebb tidal delta in the ocean domain affected by local waves; and a deep channel (28 m depth) running between them. At the inward shallow part of Anegada Bay, the flood tidal delta emerges during low tide. Elongated sand bars are formed by a reduction in the capability for sediment transport caused by widening of the channel section. The adjacent coastline is the predominant sand source, providing the sediment transported by tidal currents. Where the channel narrows, sand accumulates and a subaqueous 3-D dune field is formed in the central part of the channel. This 3-D dune field deserves special attention, as stated in detail below. Towards the mouth, the amount of granular sediment begins to decrease and the underlying hard lithology is exposed in the inlet throat, acting as a hard subsurface for ebb and flood tidal delta. Laterally, the adjacent southern coastline formed by gravel probably imposes a further constraint. These factors must contribute to the stability of the larger tidal channel and the inlet throat.

Table 1
Characteristics of dunes showed in Fig. 6.

	Angle	Height	Spacing
a	91	25–40	7–8
b	94	15–25	8
c	94	20–35	8
d	105	15–40	5–8
e	107	15–30	5–8

The ebb flow, characterized by large velocities (1.8 m s^{-1} maximum), has great erosive potential, leading to a deep channel almost free of an unconsolidated sediment cover. Due to the limited cross-section of the constricted inlet throat, the ebb flow is confined in a deep and narrow channel, which produces significant flow acceleration, forming an ebb-jet that outflows onto the ebb-tidal delta. The morphology of the ebb-tidal delta is essentially determined by the relative importance of the waves versus tidal energy (Oertel, 1975) and the features are governed by the dynamic balance between these two forces. Thus, shoals forming the ebb delta migrate downdrift due to the local residual southwestward-directed wave-driven flow, deflecting the ebb currents to the south. Consequently, the shoals rotate clockwise.

Where sufficient sand is available, the strong tidal currents in San Blas inlet can form large dunes. The largest dunes (5 m in height and >100 m in spacing) were present in the deeper parts of the channel (25 m depths) at the southern border of the field. There, the 'full-beddedness' (sediment availability used as dune descriptor of third order in the classification of Ashley, 1990) influences dune formation. Beyond this zone there is no more dune formation, giving a flat base in dune trough. This is due to sediment starvation, as described by Dalrymple and Rhodes (1995) and also identified by Gómez et al. (2010) in the Bahía Blanca estuary.

Dunes have a relatively complex 3-D pattern mainly in the center of the surveyed area. Dune height also typically decreases at the field border, giving way to rippled sand flats (northeastern edge). In addition, our results agree with the observations of Dalrymple and Rhodes (1995) related to the good lateral continuity that tidal 3-D dunes exhibit under reversing flow. The angle between crest line and channel direction is greater (105°–107°) for small dunes formed among larger dunes than those that are unconfined (94°). This might be due to the deflection of the near-bed flow caused by the three-dimensional shape and oblique orientation of the larger dunes, as was pointed out by Sweet and Kocurek (1990). Also, Maddux et al. (2003) demonstrated that a significant amount of momentum flux over the dune was transformed into secondary currents induced by topographic forcing due to the three-dimensionality in dune height that leads to a deflection of the small bedforms.

We found that the majority of dunes are symmetrical. Only on the northeastern edge of the field, dunes are nearly asymmetrical with the lee side oriented towards the inner bay. Assuming gradual, continuous unidirectional migration over the 9-month period, the asymmetry is probably related to the minor magnitude of dunes, where there is a reduced quantity of sand available to be moved by the high flood currents (predominantly on the northern flank).

It is important to note the contrasting dune migration sense within the field, as dunes migrate towards the inlet mouth except along the strip on the northern side where they migrate towards the inner zone (Fig. 7). Although Dalrymple and Rhodes (1995) affirmed that symmetrical dunes exist in areas where there is no net sediment transport in a particular direction, the dunes found to be migrating

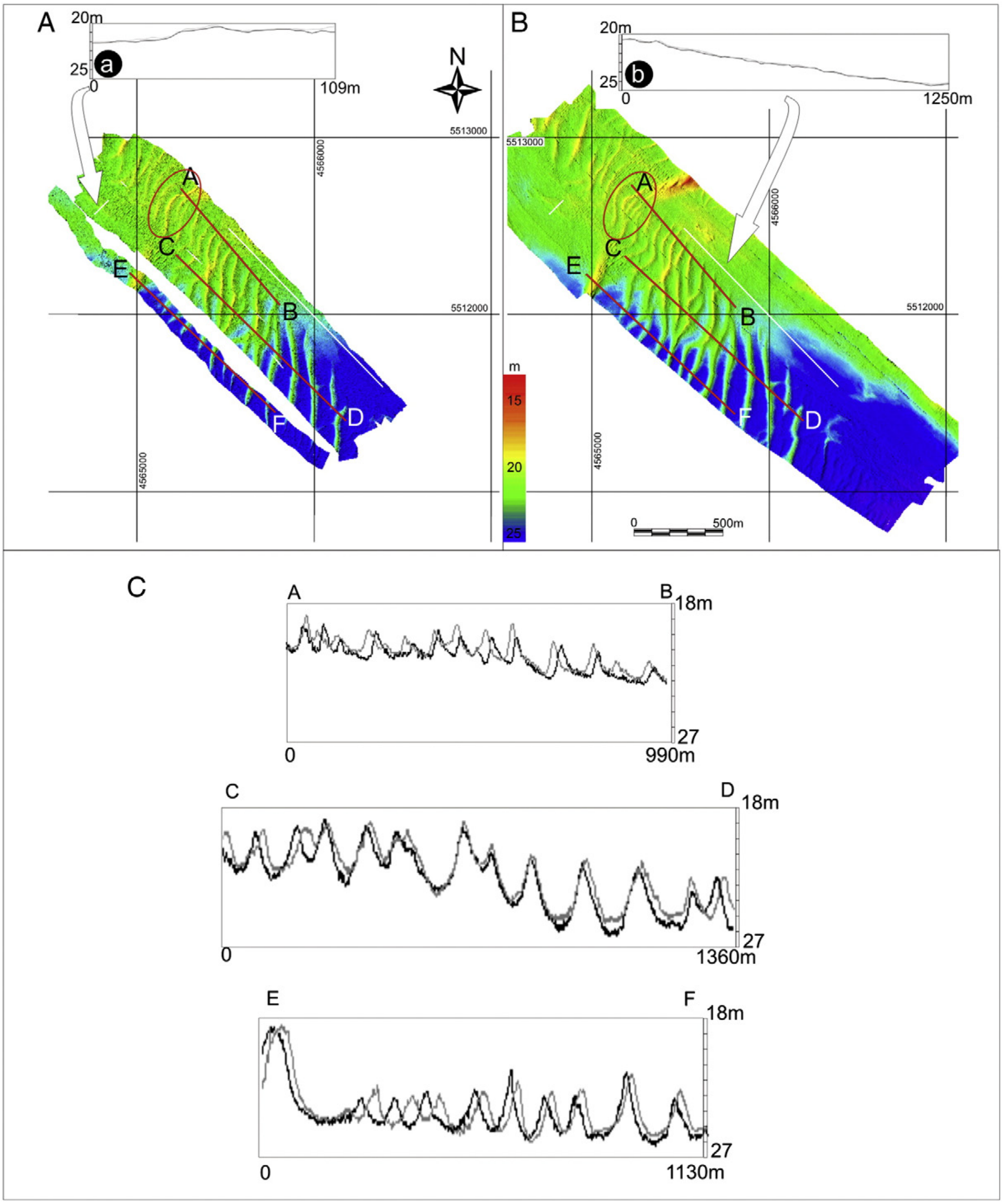

Fig. 6. (A) Morphological dune map obtained on October 2008. (B) Morphological dune map obtained on July 2009. Profiles (a) and (b) are control tracks. The circle points out the accentuation in sinuosity after nine months. (C) Different topographic profiles showing the migration of dunes. The dark line indicates the 2008 survey; the gray line, the 2009 survey.

outwards are symmetrical and maintain the same size after the displacement, thus indicating a net sediment transport direction. The measured migration rates for large dunes on the northern side of the field reached 15.7 m year^{-1} inwards through the bay, whereas very large and large dunes in the center of the field show a migration rate of 21.7 m year^{-1} towards the opposite side. It is also important that the fastest dunes located at the southern edge of the field reached 26.5 m year^{-1}, probably due to sediment starvation. All these values are in agreement with the compilation reported by Dalrymple and Rhodes (1995) who indicate migration rates for large and giant dunes ranging from one to several tens of meters per year.

The different displacements of the crest line dunes all over the field are easily identified in Fig. 7. The two factors controlling dune orientation are the variable current directions and the non-uniform rate of migration, which may operate independently or simultaneously in a tidal environment (Dalrymple and Rhodes, 1995). The effects of non-uniform conditions are likely to dominate in straight channels such as San Blas. Along-crest variation in net sediment discharge and/or bedform height will lead to different migration speeds and to oblique orientations relative to the effective current and net transport directions. This process probably operates in accentuating the sinuosity of 3-D dunes (see the circle on Fig. 6). The orientation of the crest lines depends on

Table 2
Displacement of dunes measured at northern (A), southern (B) and middle (C) areas.

n	A	B	C
1	16	24	21
2	8	11	40
3	10	12	30
4	7	15	20
5	15	20	13
6	10	18	14
7	14	17	19
8	19	20	10
9	19		9
10	6		19
11	6		

the precise cross-flow distribution of depth, current speed, and dune height; both inward and outward facing orientations are possible (Dalrymple and Rhodes, 1995). It is probable that the in-line inflections or kinks that are sometimes observed in the crests of larger dunes are the result of along-crest changes in the relative influence of height and sediment discharge on migration speed. Also, the secondary currents present between two large dunes might produce migration in different directions to that of a single dune crest.

To detect the difference between the erosive and accumulative areas, two maps were subtracted (Fig. 8). In dunes migrating outwards, the erosive areas are recognized immediately up-drift of the accretionary ones in irregular patches, whereas the opposite occurs on the northern strip. A line separating both zones of differing direction of dune migration can be drawn. This pattern closely matches the current dynamics of the zone, where higher flood speeds occur over the northern flank, while higher ebb speeds are present on the southern one.

Finally, it is possible to notice that dune morphology (height and spacing) does not alter much in spite of dune displacement over the nine months that had elapsed between both bathymetric surveys (Fig. 6). These results match with that found by Venditti (2003) who performed laboratory investigations into the effects of dune three-dimensionality on flow structure in which dune planform curvature was altered, but crest height and the three-dimensional volume of the dunes were maintained. Also, in a comparable manner as Venditti (2003), the San Blas channel dynamics (flood on the northern side and ebb on the southern side) produces preferential sediment pathways that conduct to planform curvature of the crest lines. This control of sediment transport by crest line curvature is probably manifested within the patterns of crest line bifurcations and junctions.

5. Summary and conclusions

At present, all studies on submarine dunes had assumed that the net sediment transport direction is evidenced by the dune's asymmetry, which migrates consequently in such a direction. However, results from this study show that large and very large dunes present in the middle of San Blas channel, with a migration rate up to 21 m year^{-1} outward from the channel, have a symmetrical cross-section. Due to the occurrence of secondary currents, the sediment eroded on the stoss accumulates on the lee face in irregular patches giving place to sinuous crest lines. Only on the northern limit of the dune field, where smaller dunes occur, might they migrate inward of the the channel at a minimum rate of the entire field (15.7 m year^{-1}) and show a slight asymmetrical cross-section.

Dune directions of migration in the studied area are strictly related to tidal currents, since maximum tidal currents across the channel show different patterns. The maximum ebb currents dominate in the

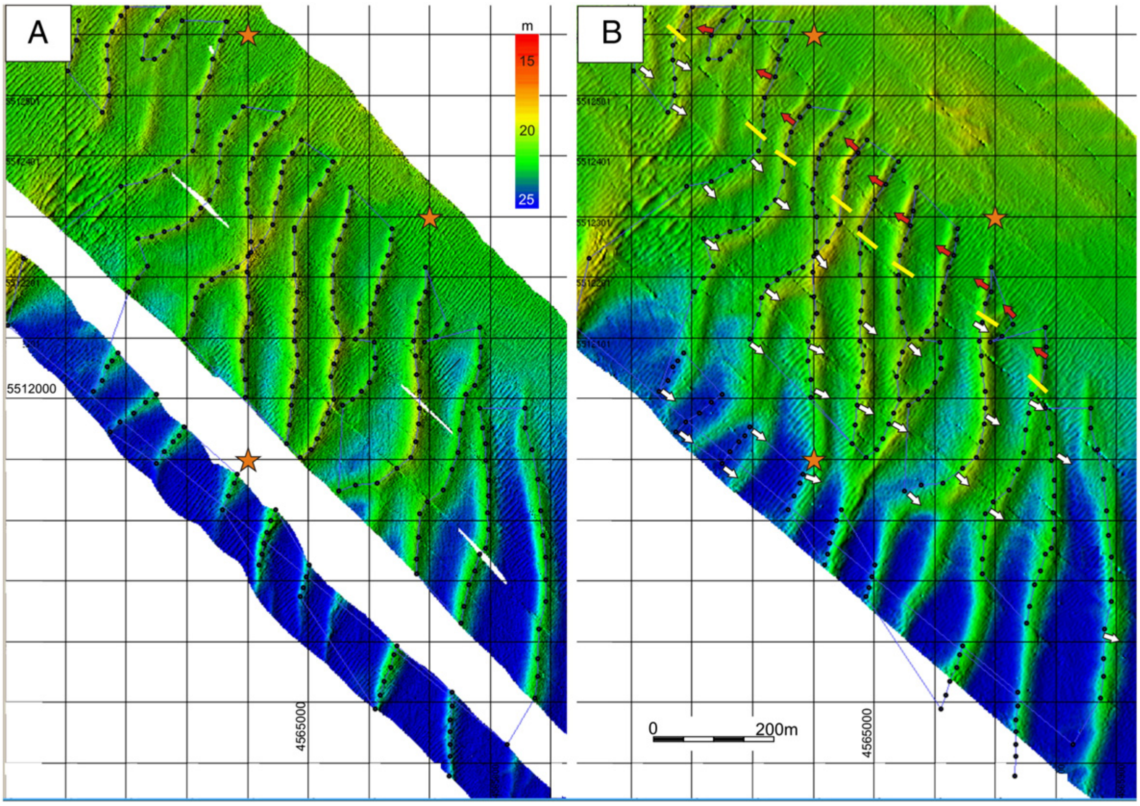

Fig. 7. Morphological dune map obtained on (A) October 2008, (B) July 2009. Crest points from October 2008 were superimposed on the map obtained from July 2009 to indicate the crest migration. White arrows indicate outward migration based on the displacement of the crest line. Colored arrows indicate inward migration. The segments show the point with no movement of the crest line. The stars point out the same coordinate.

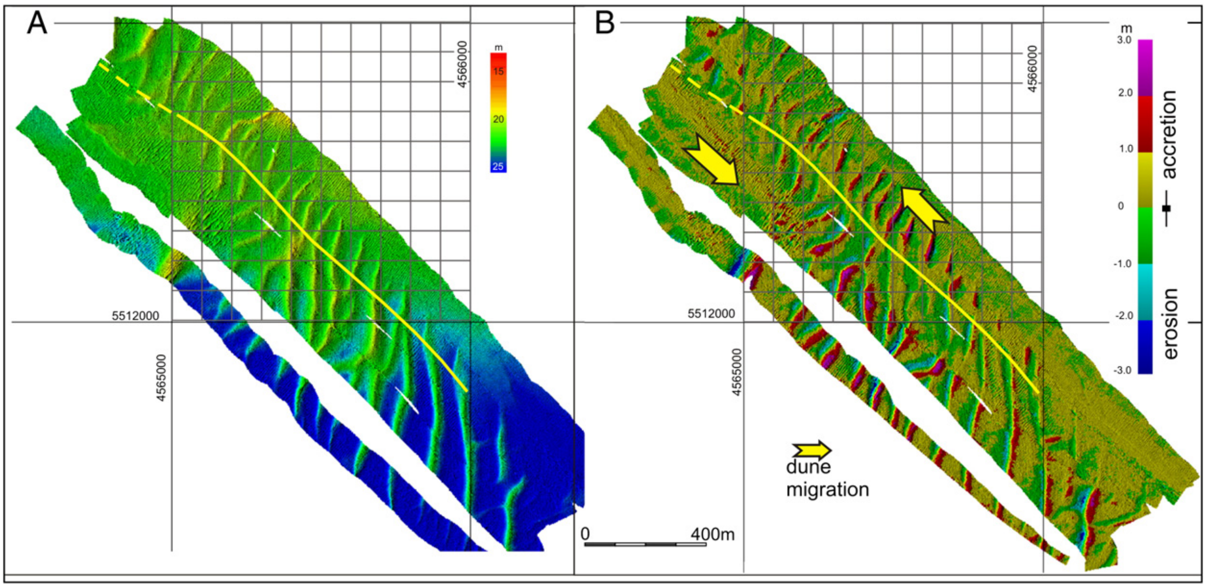

Fig. 8. (A) Map obtained on October 2008. (B) Map showing erosional and accretionary zones by subtracting maps. Arrows indicate direction of dune migration. The inferred line separating both zones of opposite migration is shown on both maps.

central and southern areas while flood maximum currents dominate on the northern flank.

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