Short and long term evolution of deep giant submarine dunes in continental shelf environment: the example of the "Banc du Four" (Western Brittany, France)

Marcaurelio Franzetti [(1)], Pascal Le Roy [(1)], Thierry Garlan [(2)], Christophe Delacourt [(1)], Rémy Thibaud [(3)], Romain Cancouet [(1)], David Graindorge [(1)], Christophe Prunier [(1)] and Alexey Sukhovich [(1)]

1. Université Européenne de Bretagne Occidentale, UMR-6538 Domaines Océaniques, IUEM / CNRS Place Copernic, 29280 Plouzané, France - marcaurelio.franzetti@gmail.com
2. SHOM, DOPS/HOM/REC-CFuD/Sédimentologie 13, rue du Chatellier 29228 Brest, France
3. Ecole Navale, IRENav BCRM Brest, CC 600, 29240 Brest, France

Abstract

The deep sandwave dynamics is still in debate. Understanding the migration processes and the resulting evolution of their 3D internal architecture are scientifically challenging. To address these questions we realized two swath bathymetry surveys complemented with seismic reflection across the large sandwaves field named "Banc du Four". It is located offshore the Western Brittany and is composed of more 500 dunes. Some of the dunes' wavelengths and heights exceed 1000m and 30m respectively placing them among the largest dunes ever described. Equilibrium laws obtained from our morphological analysis are not completely in agreement with those described in previous studies of similar structures in shallow waters. Relatively high migration velocities on deep continental shelves (from 3 to 20m.yr-1) attest of their still present dynamical equilibrium. Internal-external morphological and kinematical analyses show the existence of two different dynamic regimes. Interpretation of the seismic reflection data allowed to reconstruct long-term evolution of the sandbank and the establishment of progressive connections between stepped submarine channels and tidal dynamics during the last sea-level rise.

1. INTRODUCTION

Seabed is often covered with rhythmic sandy bedforms, the marine dunes, which are particularly wide-spread on macro-tidal continental shelves. According to Ashley (1990) and Berné et al. (1993), dunes are classified by their size (wavelength): small (0.04-0.25m), medium (0.25-0.44m), large (0.44-2.8m) and giant (>2.8m). Those are elongated bedforms, with angular variations frequently reaching up to 20°, perpendicular to the main current (Hulscher and Van den Brink, 2001). The latter ones differ from sandbanks which are defined as flow-parallel bedforms or slightly oblique (<30°) to the peak of tidal flow direction (Le Bot, 2001) and are also characterized by much larger sizes (>1000m large).

Morphology dunes parameters (wavelength, height and depth) are commonly correlated in order to determine universal relationships. Flemming (1988) gives an evidence of the existence of a geometrical equilibrium relationship between λ and h ($h=0.0677\lambda^{0.8098}$) and defines an upper height limit ($h_{max}=0.16\lambda^{0.84}$). However, recent studies on giant-deep dunes tend to invalidate this limit (Barrie et al., 2009; Van Landeghem et al., 2009). As Allen (1968) observed an increase of h in accordance with D, Francken et al. (2004) calculated another upper height limit ($h_{max}=0.25P$). Other studies (Werner et al., 1974; Van Landeghem et al., 2009) have produced contradictory evidence and have demonstrated that this relationship does not apply in general cases (Flemming et al., 2000).

Sandbodies are formed in response to the interaction between sedimentary characteristics and local hydrodynamics regime (Allen, 1968). It is usually assumed that migration velocities of dunes decrease as their size increases (Ernstsen et al., 2006). However, inverse correlations have been observed (Garlan, 2004). Marine dunes tend to migrate in the direction of the residual current by acquiring asymmetric shapes facing the same direction (Hulscher and Dohmen-Janssen, 2005). Knaapen (2005) uses the degree of asymmetry to estimate their direction and their migration rates.

However, some field observations show asymmetries opposed to residual currents (Besio et al., 2004) and migrating directions (Van Landeghem et al., 2012).

Internal geometries of sandbodies partially reflect their paleo-morphologies. Indeed, the recognition of internal dune structures allows a reconstitution of depositional environments and processes on an annual-decadal timescale (Morelissen et al., 2003).

Berné et al. (1993) describe three orders of boundaring surfaces: (1) first order surfaces which are sub-horizontal and correspond to the erosional overlapping of small sandwaves superimposed

(Berné, 1991) (2) second order surfaces which dip in direction of lee-side and correspond to an erosive process of wind-current and wave-storm (Le Bot and Trentesaux, 2004) (3) third order surfaces, which are more inclined than the latter ones, and result from the alternation of avalanche phases and “sandy rainfalls” (Berné, 1991). Allen (1980) suggests that the layout of internal units is led to the tidal asymmetry degree.

2. DATA AND METHODS

The north Iroise Sea connects the English Channel and the North Atlantic Ocean on the western Brittany’s continental shelf. The hydrodynamics is strong with tidal current velocities reaching up to $4m.s^{-1}$ (Hinschberger, 1962) and storm waves regularly exceeding 4m (Dehouck, 2006). The study area consists in a wide Northward opened triangular bay, bounded to the East by coastal reefs and to the South and West by the Molene-Ushant Archipelago. The island belt is interrupted by two narrow and shallow channels, the Fromveur channel (50m b.s.l.) and the Four channel (10m b.s.l.). The “Banc du Four” is located 100m b.s.l. in the middle of the bay (Fig. 1). The sandbody has been the subject of little investigation (Hinschberger, 1962) up to now.

DTMs were obtained by two multibeam echosounders (MBES) bathymetric surveys (Fig. 2). The Evalhydro2009 campaign, carried out in February 2009 by SHOM from the board R/V “Pourquoi-Pas?”, yielded a DTM of 5m resolution. And the AlbertGeo2010 campaign, carried out in August-September 2010 by IUEM from the board R/V “Albert Lucas” yielded four DTMs (A to D) of 2m resolution. Internal sandbodies structures were investigated by seismic reflection acquisition. SHOM conducted very High Resolution (VHR) seismic profiles with SIMRAD EM120 CHIRP on R/V “Beautemps-Beaupré” in November 2010 (Daurade2010). HR seismic profiles were carried out by IUEM on R/V “Côtes de la Manche” with sparker (250 Joules) mono and multi-channels during several surveys GeoBrest (2005, 2006, 2010 and 2012).

Morphology dunes parameters were obtained either manually or automatically on bathymetric DTMs. Wavelength λ, lee side length Ls and height h were found manually from at least three 2D cross-sectional profiles perpendicular to the waves’ crests. Crest depth D and dip direction of a lee side α are defined automatically by zonal statistics. The asymmetry A is defined as
(λ 2Ls)/λ according to Knaapen (2005).

Two different methodologies were used to measure dunes’ migration between February 2009 (EvalHydro2009) and August-September 2010 (AlbertGeo2010) in zone D: (1) firstly, the crosscorrelation, which is a rasterial technique, calculates migration vectors from the search of similar shapes between two grids obtained for two different times t1 and t2 (Delacourt et al., 2004; Duffy and Hughes-Clarke, 2005; Buijsman and Ridderinkhof, 2008) and (2) then, the spatiotemporal graph approach is based on an entitiesrelations conceptual model and on geometrical measurements between geographical entities (crests of dunes) related by filiation or sptatiotemporal links (Del Mondo et al., 2010; Thibaud et al., 2012). The results of these two methods were then compared.

3. RESULTS

The “Banc du Four” is a series of more than 510 bedforms extending between 70 and 105m b.s.l. It is characterized by a sandbank flanked by two dune fields, which define a V shape (Fig.2). The sandbank covers an area of 4x2km2 ranging between 35 to 90m b.s.l. It is nearly symmetrical, with a flattened crest aligned to the East-West direction. To the south, it is preceded by a giant asymmetric straight dune (λ=1050 m, h=32 m, width=2000 m) oriented towards the Southwest direction. In one hand, the northwestern dune field is characterized by dunes decreasing in size (between 0.02 to 30m high and 10 to 600m wavelength) while increasing in depth (50 to 105m b.s.l.) as one goes away from the sandbank. They are generally asymmetric with a flexing of the upper part of the crests and polarity directions that rotate clockwise (from Southwest to Northeast) as the distance to the Northwest increases. In the other hand the northeastern dune field is characterized by giant asymmetric dunes (between 0.02 to 20m high and 10 to 500m wavelength) and an increasing depth as one goes away from the sandbank. Their morphologies delineate two distinct zones: (1) in the western part, dunes are nearly straight and oriented towards the Southwest (2) in the eastern part, dunes are smaller, yet with a greater sinuousness (even barkanoid) and inversely oriented (towards the Northeast). The separation of the latter ones manifests itself by a well-marked shear zone.

The dunes' morphological parameters analysis of "Banc du Four" gives interesting results. The geometrical equilibrium relationship between λ and h ($h=0.0121\lambda^{1.1902}$, $r^2=0.75$) has a similar trend to that of Flemming (1988) but with a steeper positive slope. Furthermore, some measurements values exceed the upper limit of Flemming (1988).

One can also assess that the calculated relation between h and D is not accurate ($h=13156.103D^{-3.4595}$, $r^2=0.3$). Yet, the height of the dunes decreases as the crest depth increases, this trend being opposed to Allen's observations (1968). Moreover, for some dunes, the ratio of h and D exceeds the upper limit calculated by Francken et al. (2004).

Cross-correlation parameters used were 32 pixels for the search window and 8 pixels for the shape matrix. Only migration vectors associated to SNR above 0.99 and magnitude vector greater or equal to 5m were kept. The calculated dune migration rates vary between 3 and 20m.yr-1. At 75%, the migration directions correspond to morphological directions of dunes with an angular spacing lower than 30°. As for the morphological analysis, the dune migrations delineate the same two zones: (1) the western part characterized by lower velocities (6m.yr^{-1} mean) and motion directions towards the Southwest (2) the eastern part characterized by higher velocities (12 m.yr-1 mean) and an opposite migration direction (towards the Northeast). Here again, one can identify a central shear separation with no preferential motion direction. Similar dune migration results were obtained with the spatiotemporal graphs method (deviations less than 10% for migration rates and 15% for migration directions).

The analysis of internal geometry of Zone D dunes was performed with seismic CHIRP and sparker profiles. The observed reflectors can be split in two groups characterized by different layouts. The first group is composed of oblique third order reflectors parallel to the dune lee-slope and prograding towards the latter. These foresets downlap a first order (subhorizontal) reflector which is the prolongation of the next dune's stossside. According to Reineck and Singh (1980), this

geometry is due to dune migration which proceeds by successive avalanches at the lee-side and prograding on the next dune's stoss-side. The reflectors of second group form small units made of first and third order reflectors crosscut by slightly oblique second order reflectors dipping in direction of lee-side (Ferret et al. 2010). These units are accumulated vertically whithin the dune.

Internal structures of sandbank were derived from seismic sparker profiles (Fig. 3). Six different units have been individualized and numerated in chronological order. The first unit (U1) is the deepest and smallest one, localized in the center of the sandbank and lies on the substratum. The second unit (U2) is bigger, aggrades and progrades partially on the previous unit toward the Northwest. The third unit (U3) rests on previous unit side and progrades toward the WNW. The fourth unit (U4) aggrades and progrades towards the WNW with the same area that the sandbank itself. The fifth unit (U5) aggrades in the WNW part of the sandbank. The last active unit (U6) covers the entire sandbank with an aggrading component in the northwestern part.

4. DISCUSSION

Morphology parameters relationship results of "Banc du Four" are different from other authors' studies. Flemming (1988) described well the general trend of increasing height as wavelength increases, without determining a universal law for the geometrical equilibrium relationship and an upper height limit. This assessment is consistent with other observations (Barrie et al., 2009; Van Landeghem et al., 2009). Moreover, the inverse relationship between height and crest depth observed here is contrary to that of Allen (1968) and some height values measured exceed the upper limit established by Francken, et al. (2004). Here again, these observations are consistant to similar studies (Werner et al., 1974; Flemming et al., 2000; Van Landeghem et al., 2009). The non universality of morphology parameters relationship can be linked to the failure to take into account particular environments such as deeper waters and highlights that the complex physical mechanisms of dunes' forming are still poorly known.

The migration directions of dunes in Zone D are in agreement with their morphological directions (Hulscher and Dohmen-Janssen, 2005). The dunes' dynamic study clearly shows two opposing dynamic sets in shearing. This is in accordance with numerical models of tidal residual current near the bottom (Guillou, 2007): (1) western part is characterized by a clockwise current eddy (2) eastern part is characterized by a tidal coast current oriented toward the Northeast. This spatial segmentation is also found in the analysis of morphodynamical parameters relationships: (1) in western part, the velocity increases with size (in agreement with Garlan, 2004) and asymmetry (in agreement with Knaapen, 2005) and (2) in the eastern part, the velocity decreases with an increase of dune size (in agreement with Ernstsen et al., 2006) and asymmetry. To this is added the difference of internal geometries observed with seismic profiles: (1) in western part, dunes are mainly formed by accumulation of prograding avalanche foresets in forward direction and (2) in eastern part, internal dunes' geometry consists in an alternative superposition of smaller dunes with different degrees of asymmetry. Based upon the model of internal structures of Allen (1980), we can assume that there is an asymmetry difference of tidal currents which induces two different dunes' dynamics: (1) in the western part, the clockwise current eddy leads to an asymmetric hydrodynamics regime and (2) in the eastern part, the tidal coast current presents a less asymmetrical behavior.

The internal structuration of sandbank reflects major developments over time in relation with the last sea-level rise and the establishment of progressive connections between stepped submarine channels and tidal dynamics. The U1 unit marks the first formation stage of the "Banc du Four" with the establishment of a small sandy structures (most likely a small sandbank or a dune field) in shallow water. At this time, the sand structure was no deeper than 80m below the current sea level (b.c.s.l.) and the north Iroise Sea could look like a wide open bay toward Northwest. The U2 unit marks a strong change of the sedimentary dynamics which can be explained by the opening of one of the South channels when the sea level was above 50m b.c.s.l. This episode is followed by a gradual displacement of the sedimentation in Northwest direction (U3, U4 and U5) due to the submersion of the Molene-Ushant Archipelago. The recent stabilization of coastline may explain the low mobility of sedimentation (U6).

5. ACKNOWLEDGMENT

This worked was founded by the Direction Générale de l'Armement (DGA). The authors are very grateful to the crew of vessels "Albert Lucas" and "Côtes de la Manche". They also thank Guillaume Fromant who has vetted this paper..

6. REFERENCES

Allen, J.R.L., 1968. The nature and origin of bed-form hierarchies. Sedimentology 10: 161-182.

Allen, J.R.L., 1980. Sand waves: A model of origin and internal structure. Sedimentary Geology, 26(4): 281-328.

Ashley, G.M., 1990. Classification of large-scale subaqueous bedforms: a new look at an old problem. Journal of Sedimentary Petrology 60: 160-172.

Barrie, J.V., Conway, K.W., Picard, K., Greene, H.G., 2009. Large-scale sedimentary bedforms and sediment dynamics on a glaciated tectonic continental shelf: Examples from the Pacific margin of Canada. Continental Shelf Research 29: 796-806.

Berne, S., 1991. Architecture et dynamique des dunes tidales. PhD Thesis, University of Lille 1, Villeneuve-d'Ascq: 295.

Berne, S., Castaing, P., Le Drezen, E., Lericolais, G., 1993. Morphology, internal structure, and reversal of asymmetry of large subtidal dunes in the entrance to Gironde estuary (France). Journal of Sedimentary Petrology 63: 780-793.

Besio, G., Blondeaux, P., Brocchini, M., Vittori, G., 2004. On the modeling of sand wave migration. Journal of Geophysical Research 109.

Buijsman, M.C., Ridderinkhof, H. 2008. Long-term evolution of sand waves in the Marsdiep inlet. I: High-resolution observations. Continental Shelf Research 28: 1190-1201.

Dehouck, A., 2006. Observations et conditions d'apparition de croissants de plage sur les littoraux de la mer d'Iroise. Norois 20: 7-16.

Delacourt, C., Allemand, P., Casson, B., Vadon, H., 2004. Velocity field of the “La Clapière” landslide measured by the correlation of aerial and Quick-Bird satellite images. Geophysical Research Letters 31: 1-5.

Del Mondo, G., Stell, J.G., Claramunt, C., Thibaud, R., 2010. A graph model for spatio-temporal evolution. Journal of Universal Computer Science, 16: 1452-1477.

Duffy, G.P., Hughes-Clarke, J.E., 2005. Application of spatial cross correlation to detection of migration of submarine sand dunes. Journal of Geophysical Research 110: 10.

Ernstsen, V.B., Noormets, R., Winter, C., Hebbeln, D., Bartholomä, A., Flemming, B.W., Bartholdy, J., 2006. Quantification of dune dynamics during a tidal cycle in an inlet channel of the Danish Wadden Sea. Geo-Marine Letters 26: 151-163.

Ferret, Y., Le Bot, S., Tessier, B., Garlan, T., Lafite, R., 2010. Migration and internal architecture of marine dunes in the eastern English Channel over 14 and 56 years intervals: the influence of tides and decennial storms. Earth Surface Processes and Landforms 35: 1480-1493.

Flemming, B.W., 1988. Zur Klassifikation subaquatischer, strömungstransversaler Transportkörper. Bochumer Geologische und Geotechnische Arbeiten, 29: 93-97.

Flemming, B.W., 2000. The role of grain size, water depth and flow velocity as scaling factors controlling the size of subaqueous dunes. A.

Trentesaux, T. Garlan (Eds.), Marine Sediment wave Dynamics, Proceedings of and Internaltional Workshop held in Lille, France, 23-24 March 2000, University of Lille 1, Lille: 55-60.

Francken, F., Wartel, S., Parker, R., Taverniers, E., 2004. Factors influencing subaqueous dunes in the Scheldt Estuary. Geo-Marine Letters 24: 14-24.

Garlan, T., 2004. Apports de la modélisation dans l'étude de la sédimentation marine récente, HDR thesis, Université d'Angers: 158.

Guillou, N., 2007. Rôles de l'hétérogénéité des sédiments de fond et des interactions houle—courant sur l'hydrodynamique et la dynamique sédimentaire en zone subtidale - applications en Manche orientale et à la pointe de la Bretagne. PhD thesis, Université de Bretagne Occidentale: 469.

Hinschberger, F., 1962. Résultats de 14 stations hydrologiques dans l'Iroise et à ses abords. Comptes Rendus de l'Académie des sciences 255 : 2629-2631.

Hulscher, S.J.M.H. & Van den Brink, G.M., 2001. Comparison between predicted and observed sand waves and sand banks in the North Sea. Journal of Geophysical Research 106: 9327-9338.

Hulscher, S.J.M.H. & Dohmen-Janssen, C.M., 2005. Introduction to special section on marine sand wave and river dune dynamics. Journal of Geophysical Research 110: 6.

Knaapen, M.A.F., 2005. Measuring sand wave migration in the field. Comparison of different data sources and an error analysis. Journal of Geophysical Research, Earth Surface 110: 152-159.

Le Bot, S., 2001. Morphodynamique de dunes sous-marines sous influence des marées et des tempêtes. Processus hydro-sédimentaires et enregistrement. Exemple du Pas-de-Calais. PhD thesis, Université de Lille 1: 300.

LeBot, S., Trentesaux, A. 2004. Types of internal structure and external morphology of submarine dunes under the influence of tide- and wind-driven processes (Dover Strait, northern France). Marine Geology 211: 143-168.

Morelissen, R., Hulscher, S.J.M.H., Knaapen, M.A.F., Németh, A.A., Bijker, R., 2003. Mathematical modeling of sand wave migration and the interaction with pipelines. Coastal Engineering 48 : 197–209. Reineck, H.E. & Singh, I.B., 1980. Depositional Sedimentary Environments. New York: Springer-Verlag: 22-30.

Thibaud, R., Del Mondo, G., Garlan, T., Mascret, A., Carpentier, C., 2012. A spatio-temporal graph model for marine dune dynamics analysis and representation - accepted of Journal Transactions in GIS in august 2012.

Van Landeghem, K.J.J., Uehara, K., Wheeler, A.J., Mitchell, N.C., Scourse, J.D., 2009. Post-glacial sediment dynamics in the Irish Sea and sandwave morphology: data-model comparisons. Continental Shelf Research 29: 1723-1736.

Van Landeghem, K.J.J., Baas, J.H., Mitchell, N.C., Wilcockson, D., Wheeler, A.J., 2012. Reversed sandwave migration in the Irish Sea, NW Europe: A reappraisal of the validity of geometry-based predictive modelling and assumptions. Marine Geology 295-298: 95-112.

Werner, F., Arntz, W.E., Tauchgruppe, K., 1974. Sedimentoloie und Okologie eines ruhenden Riesenrippelfeldes. Meyniana 26: 39-59.

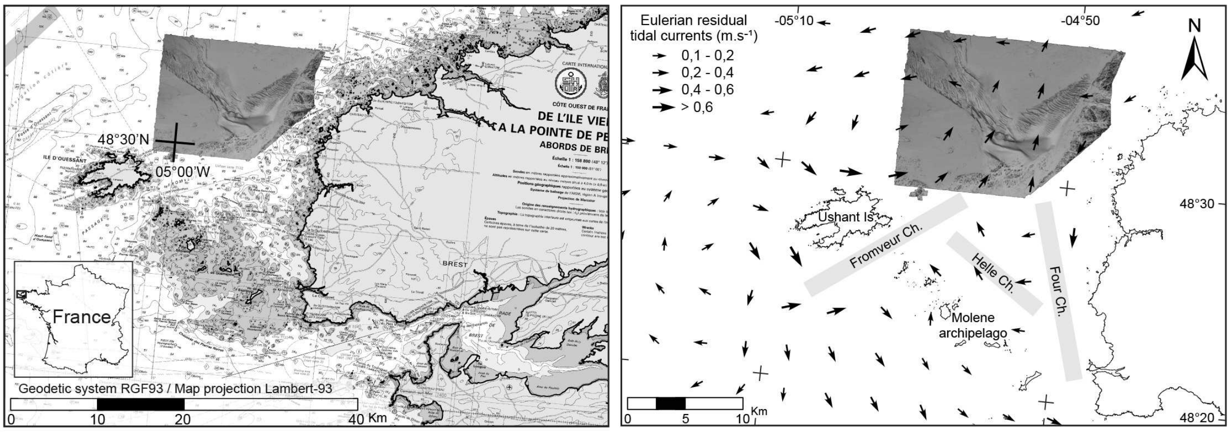

Figure 1. left) Map of the Iroise sea (situated between Brittany French coast and the Ushant-Molene Archipelago) showing the location of DTM EvalHydro2009. The study area covers 14x18 km2 with the water depth ranging up to 100 m. (right) Eulerian residual tidal currents according to PREVIMER for a tide range of 90.

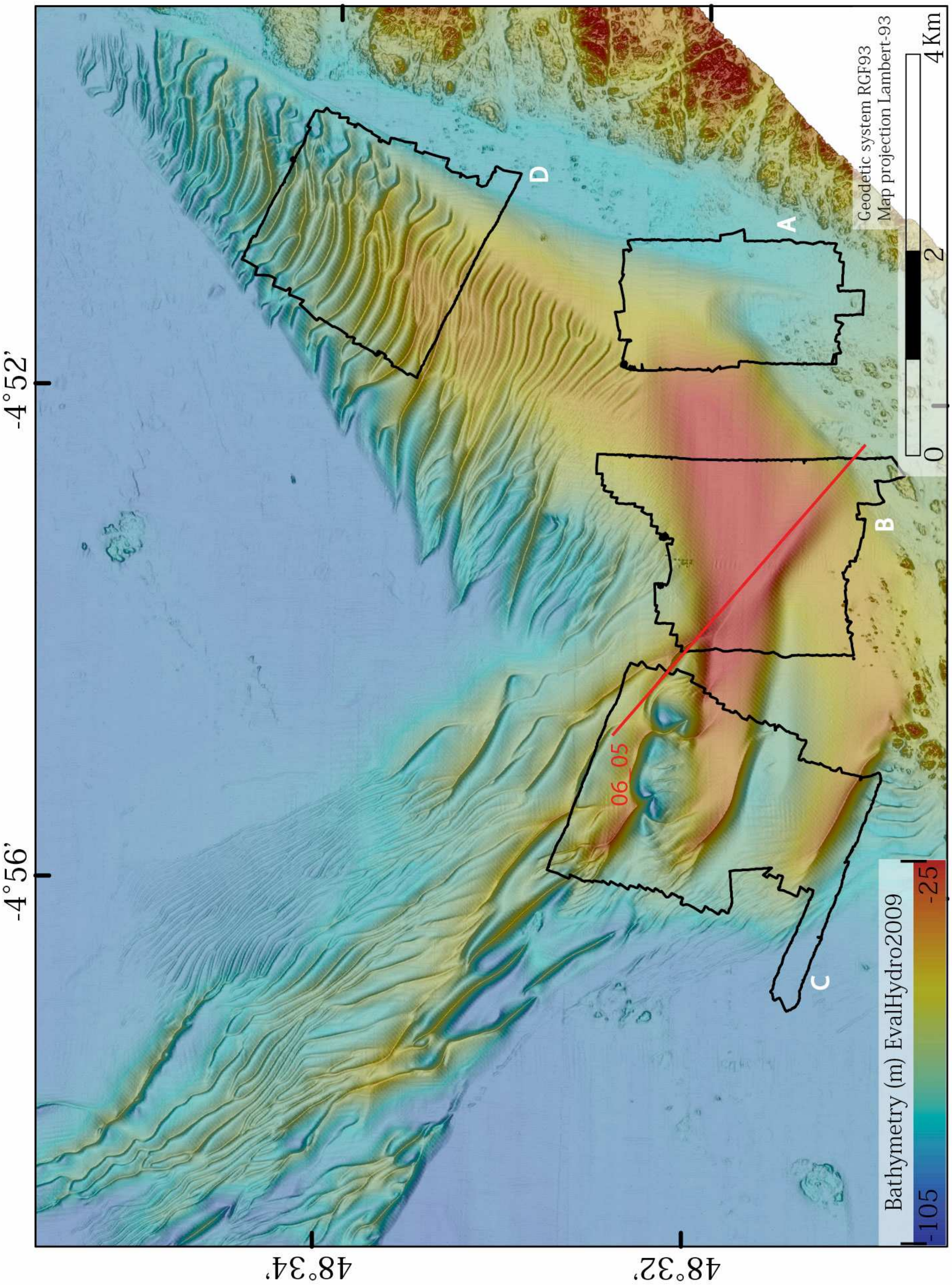

Figure 2. Bathymetry of "Banc du Four" on February 2009 defined with a 5 m resolution. Areas of AlbertGeo2010 swath surveys are outlined by black solid lines and labelled in white as A, B, C and D. Seismic sparker profile number 6 of GeoBrest2005 is located by a solid line.