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Submarine slide initiation and evolution offshore Pointe Odden, Gabon — Analysis from annual bathymetric data (2004–2009)

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ABSTRACT

Time serial bathymetric data acquired between 2004 and 2009 are used to evaluate the morphological evolution of the coastal area offshore Pointe Odden, located on the Mandji Island (Gabon). Data analysis highlights the alternation between fast sedimentation periods at shallow water depth related to intense longshore drift and catastrophic erosional events. Because of sediment overloading and slope oversteepening, small-scale instabilities are generated (successive slide scars, channel formation and growth by retrogressive erosion). However, when critical stability conditions are reached, large failures occur (2005 submarine slide). Geotechnical measurements and sedimentological analyses on the study area suggest that flow liquefaction would be the triggering mechanism of the 2005 event. Moreover, our analysis shows that the associated slide scar is rapidly filled by compensation and that failure morphology could disappear from the seafloor in about 15–20 years.

1. Introduction

Slope instabilities have been studied in many different environments all over the world (e.g. Hampton et al., 1996; Mienert et al., 2002; Masson et al., 2006; Leynaud et al., 2009 and references therein). Due to the growing development of human activities on subaqueous environments, mass-wasting on coastal and underwater slopes are considered as major geological hazards. Analyses of these events were therefore often carried out for a better understanding of geological phenomena which represent a risk for the safety to the coastline areas and offshore infrastructures (Locat and Lee, 2002, Dan et al., 2007).

Since the last decades, bathymetric surveys have become an essential component to describe and understand slope instabilities. Despite extensive works, the short-term evolution of areas subject to mass wasting is poorly documented. Although some recent studies have focused on this particular issue (Mitchell, 2005; Smith et al., 2005; Smith et al., 2007), little is known about the frequency or significance of these processes in the short term. Therefore, annual or multi-annual monitoring of sensitive coastal areas using high-resolution bathymetric data is needed to understand submarine mass wasting and prevent damages to both coastline areas and offshore infrastructures (Kulikov et al., 1996; Mulder et al., 1997; L'Heureux et al., 2010).

This study analyses bathymetric data acquired annually between 2004 and 2009 and explores the short-term sedimentary processes shaping the Pointe Odden area (Gabon) based on our interpretation of morphological changes. Geotechnical measurements were also performed on the study site in order to characterize the lithology and the mechanical properties of the sediment. From this multidisciplinary approach, we propose to explain development and potential triggers of the sedimentary processes observed during the survey period.

2. Environmental settings

The present-day climate on the Gabon basin is influenced by the permanent Atlantic monsoon (Nicholson, 1996). Annual precipitations are significant and reach 2.1 m at Port Gentil (Ondo Assoumou, 2006; Fig. 1A). Mean monthly rainfalls are close to 200 mm, except between June and September where they largely decrease (<5 mm/month).

The Ogooué River drains more than 95% of the Gabon basin (203,000 km^2, Mahé and Olivry, 1995) and constitutes the third-largest African freshwater source flowing into the Gulf of Guinea (Mahé et al., 1990). The mean annual discharge of the Ogooué River

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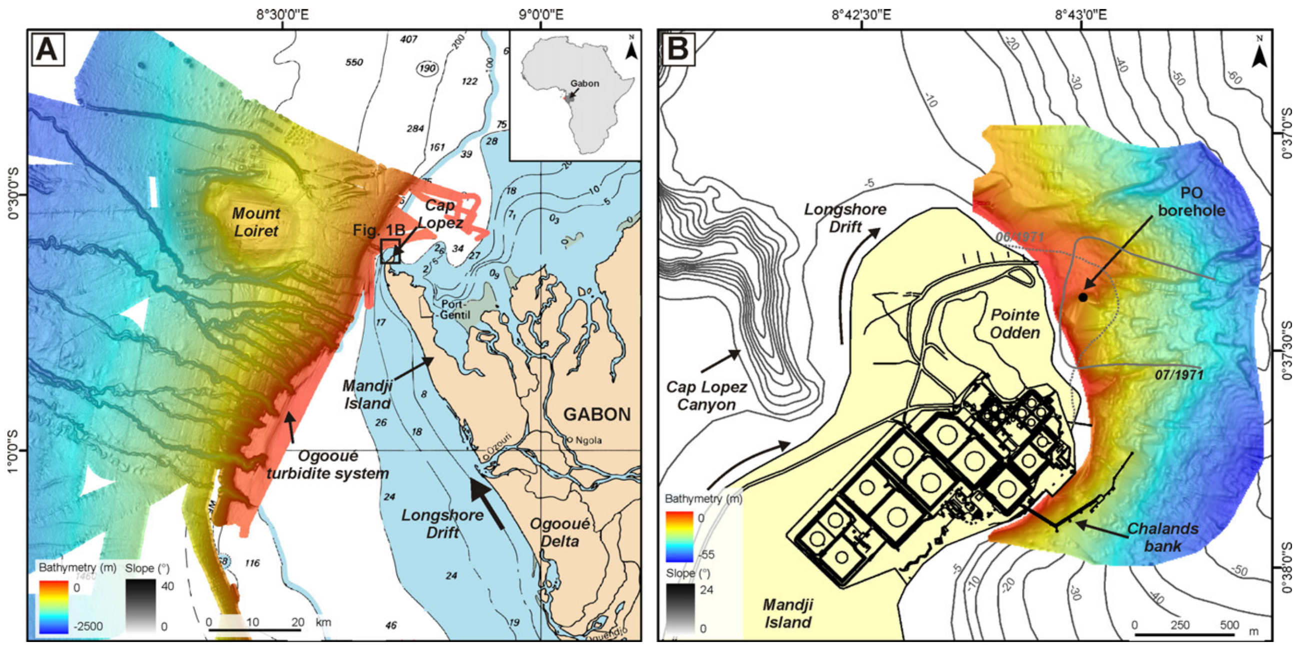

Fig. 1. A) General map showing the Ogooué Delta, the Mandji Island and the morphology of the proximal part of the Ogooué turbidite system (Gabon). General bathymetric and topographic map are modified from the chart edited by the Service Hydrographique et Océanographique de la Marine (SHOM; French Navy). B) Detailed 2009 bathymetric map of the study area (IOTA SURVEY) and location of PO borehole site. The approximate location of the coastline before the 1971 event (grey dashed line) and the extent of the associated slide scar (grey line) are represented. The general bathymetric map is modified from the chart edited by the SHOM.

at the Lambaréné hydrological station is about 4700 m^3/s (Mahé et al., 1990). The water discharge fluctuations are relatively low, ranging from 979 to 11,300 m^3/s (http://www.grdc.sr.unh.edu/). The Ogooué River forms a large delta in the south of Port Gentil, on both sides of the Mandji Island (Fig. 1A).

The Gabonese coast is affected by semi-diurnal tide, with a low spring-tide range (<1.2 m). Wave statistics based on Wane database indicate that wave conditions on the coast are characterized by a predominant direction from South to South-West, with 95% of wave directions between 175° and 205° (Actimar, 2004). The mean estimated significant wave height is 1.34 m high for a mean peak period of 11.3 s.

Reflection of these southwesterly swells causes coastal sediments to be transported northward and conducts to the rectilinear SE–NW oriented morphology of the coast (Fig. 1A). Sedimentary transport linked to longshore drift ranges between 300,000 m^3/yr and 400,000 m^3/yr (Bourgoin et al., 1963) and is responsible for the formation of the Mandji Island, a sandy spit of 50 km long located on the northern end of the Ogooué Delta (Fig. 1A). The northward transport of coastal sediments ends at the Cap Lopez, on the far north of the Mandji Island and conduces to enhanced sedimentation on Pointe Odden (Fig. 1B).

Archive photographs and bathymetric maps indicate dramatic changes of the coastline since at least the start of the twentieth century due to major slide activity on Pointe Odden (Lacasse and Boisard, 1996). The first submarine slide to be studied in detail in this area occurred in July 1971. About 310 m of the coast (97,000 m^2) disappeared into the sea, moving 1000 m offshore. The volume of the associated eroded sediment was estimated between 2,000,000 and 3,000,000 m^3 (Lacasse and Boisard, 1996). In March 1992, a new slide of lesser extent (500,000 m^3) occurred in the same area of the 1971 event. At its deepest, the slide scar was 10–12 m deep and extended around 350 m eastward. About 29,000 m^2 of land mass disappeared during this event.

3. Methods

3.1. Bathymetric data

IOTA SURVEY performed five annual springtime oceanographic surveys of Pointe Odden area between 2004 and 2009. Bathymetric data for 2004, 2006, 2007 and 2008 were acquired with an Odom Echotrac DF3200 MKII single beam echosounder whilst the 2005 data were collected with a 320M Knudsen single beam echosounder. In 2009, bathymetric data were acquired with a Seabat 7125 multibeam echosounder (Reson). During each cruise, vessel positions were recorded via DGPS. Offsets, tidal effects, sound velocity variations and swath errors that occurred during the surveys were corrected from raw data. Visual examinations and manual rejections of soundings were performed to further clean the dataset.

In order to evaluate the morphological evolution of the area surrounding Pointe Odden, bathymetric comparisons were performed using the 2004–2008 single-beam datasets. Defining the uncertainty associated with bathymetric comparison analysis is difficult and involves an assessment of many potential sources of error. Three primary factors impacting the accuracy of volume calculations have been defined after HQUSACE (2002): 1) seafloor irregularities and data density, 2) depth measurement bias errors and 3) deviations in depth observations. Although the three factors must be considered in estimating uncertainty, the relatively low density of bathymetric data due to single beam acquisition and the presence of seafloor irregularities are the most important factors influencing uncertainties in volume change estimates (Byrnes et al., 2002). This uncertainty, which relates to both data acquisition and seafloor relief, has a significant impact on data interpolation.

The interpolation error for the 2004–2008 single-beam bathymetric data was evaluated by using the depth difference between each raw sounding and its value in the associated interpolated cell for each bathymetric survey. Statistics were obtained for each survey, providing the maximum and mean error values with the associated standard deviation. This method allowed us to test various gridding interpolation methods and to establish the most significant parameters of the interpolation. In addition, the error associated with each sounding allowed us to identify remnant anomalous soundings. All the parameters obtained during these calculations, both before and after data filtering of the anomalous soundings are listed in Table 1.

From these estimated errors, a final digital elevation model (DEM) was performed for each survey, using the IDW interpolation method in ArcGIS software. The best results were obtained for a 10 m cell size with a 20 m fixed search radius, which reflects the true effective

Table 1
List of the maximum and mean interpolation errors and the associated standard deviation obtained before and after filtering of anomalous soundings for each year single-beam bathymetric dataset and from raster substraction.

Year	Number of sounding	Annual max error (m)	Annual mean error (m)	Standard deviation (m)
2004	9430	2.22	0.29	0.16
2004 (filtered)	9405	1.46	0.13	0.13
2005	78,925	30.07	0.20	0.15
2005 (filtered)	78,888	3.10	0.19	0.15
2006	63,194	2.88	0.17	0.14
2006 (filtered)	63,182	1.98	0.17	0.14
2007	84,348	4.82	0.17	0.13
2007 (filtered)	84,243	2.91	0.17	0.13
2008	128,577	12.78	0.18	0.15
2008 (filtered)	128,563	3.45	0.18	0.15
2004–2005	–	–	0.33	–
2005–2006	–	–	0.37	–
2006–2007	–	–	0.34	–
2007–2008	–	–	0.35	–
2004–2008	–	–	0.32	–

resolution of the single beam mapping system. The evolution of the sedimentary budget between 2004 and 2008 was calculated by subtracting similar DEMs extent (~1.95 km^2) to determine the bathymetric change for each grid cell. The depth difference in each cell was then multiplied by the cell surface (100 m^2) and integrated to estimate the volume difference in the whole study area and in specific regions.

Finally, we evaluated the impact of the interpolation error on the volume change estimates computed from DEM comparisons. The mean volume error was calculated by multiplying the surface of the study area by the interpolation error of the compared DEMs (Table 1). This mean volume error was then compared to the sum of the absolute volume differences on the area and normalized to obtain a percentage error. Overall, the percentage of error associated with the interpolation of the evaluation of the sedimentary budgets for the years 2004–2008 ranged from 25% to 80%. The percentage is low for years with localized and enhanced erosion/sedimentation rates (25% in 2005–2006), while it is higher with low and evenly distributed sedimentation/erosion rates on the DEM (80% for the year 2007–2008). Although the overall interpolation error suggests that the estimates should be treated with care, we mainly focus on specific areas characterized by very strong morphological evolutions and where the local interpolation error is low.

3.2. Geotechnical and sedimentological data

Geotechnical characterization was performed in 1984 onshore Pointe Odden on the PO site, presently located on the 2005 slide scar (Fig. 1B, Delft, 1984). The head of the borehole was located 3.14 m above the hydrographic zero. A cone penetration test (CPTU) was performed, giving a continuous measurement of the tip resistance (qt), sleeve friction (fs), excess pore pressure (Δu_2) and porosity. Only measurements of these parameters below the hydrographic zero are presented in this study. From the CPTU measurements, a lithological log representing normalized soil behaviour type (SBTn) was obtained (Fig. 4; Robertson, 1990). On the same site, a sediment core was collected (Delft, 1984). Even if the borehole reached a depth of 17 m below the hydrographic zero, the recovery of the core is low (~25%). Sedimentological descriptions and grain size analyses were performed on the collected core material (Delft, 1984).

4. Results

4.1. Morphological trends

4.1.1. Channel formation and extension

Comparison of bathymetric data reveals several evidences of channel formation and development. The most striking example is the landward propagation of a channel, which significantly deepened (~4 m) and widened (20–70 m) between 2004 and 2005 (Figs. 2B and 3A). The head widens towards the coast to form a funnel-shaped scarp at 5 m water depth (Fig. 2B). Net sediment loss related to the channel extension is estimated at 170,000 m^3 ± 20,000 m^3 and corresponds to an average depth increase of approximately 3 m over an area of 70,000 m^2. 2007–2008 bathymetric comparison also reveals localized erosion (Fig. 3D) inside the slide scar conducing to the lateral migration of a channel (~60 m toward the south). Enhanced deposition around the channel probably facilitated the channel migration by retrogressive erosion (Fig. 3D).

The formed channels are relatively large and deep, suggesting that these structures may endure at least for several years. However, short-lived channels are also identified (Fig. 3C and D). Bathymetric comparison reveals the formation of a small channel (depth: 3 m, width: 45 m) located between 5 and 30 m water depth (~35,000 m^3 ± 5000 m^3) around the Chalands Bank (Fig. 3C). The 2007–2008 DEM subtraction indicates that this structure is rapidly filled (~25,000 m^3 ± 5000 m^3).

4.1.2. Small-scale instabilities

Small erosional areas (<150 m width) are visible on the bathymetric comparisons (Fig. 3A and C). Despite a small extent, the mobilized volume of sediment is significant (20,000–50,000 m^3 ± 5000 m^3). They are located very close to the coast, at proximity of human installations between 0 and 20 m water depth. Run out distance of the slides is small (200 m–500 m) and conduces to lenticular shape deposits at shallow water depth. The volume of the deposits is estimated at 30,000 ± 10,000 m^3.

4.1.3. Large-scale submarine slide

Comparison of 2005–2006 bathymetric DEMs reveals the initiation of a large submarine slide on the study area (Fig. 3B). The slide scar, characterized by amphitheatre-shaped scarps extends over 1 km between 1 m and 45 m water depth (Fig. 2C). The width of the slide scar decreases downslope, from 400 m at the headwall to 170 m at 45 m water depth. The headwalls of the slide scar are up to 15 m high and show steep gradients (6–22°). The depression floor is not as steep (mean gradient: 2.8°) and has a relatively smooth seafloor relief (Fig. 2C).

Although the DEM subtraction does not show any evidence of deposits inside the slide scar due to higher erosion compared to deposition (Fig. 3B), bathymetric data show that part of the slide was deposited between 40 m and 50 m water depth within the depression (Fig. 2C). Moreover, the slide probably enhanced the partial infill of the channel located north of the scar (Fig. 3B).

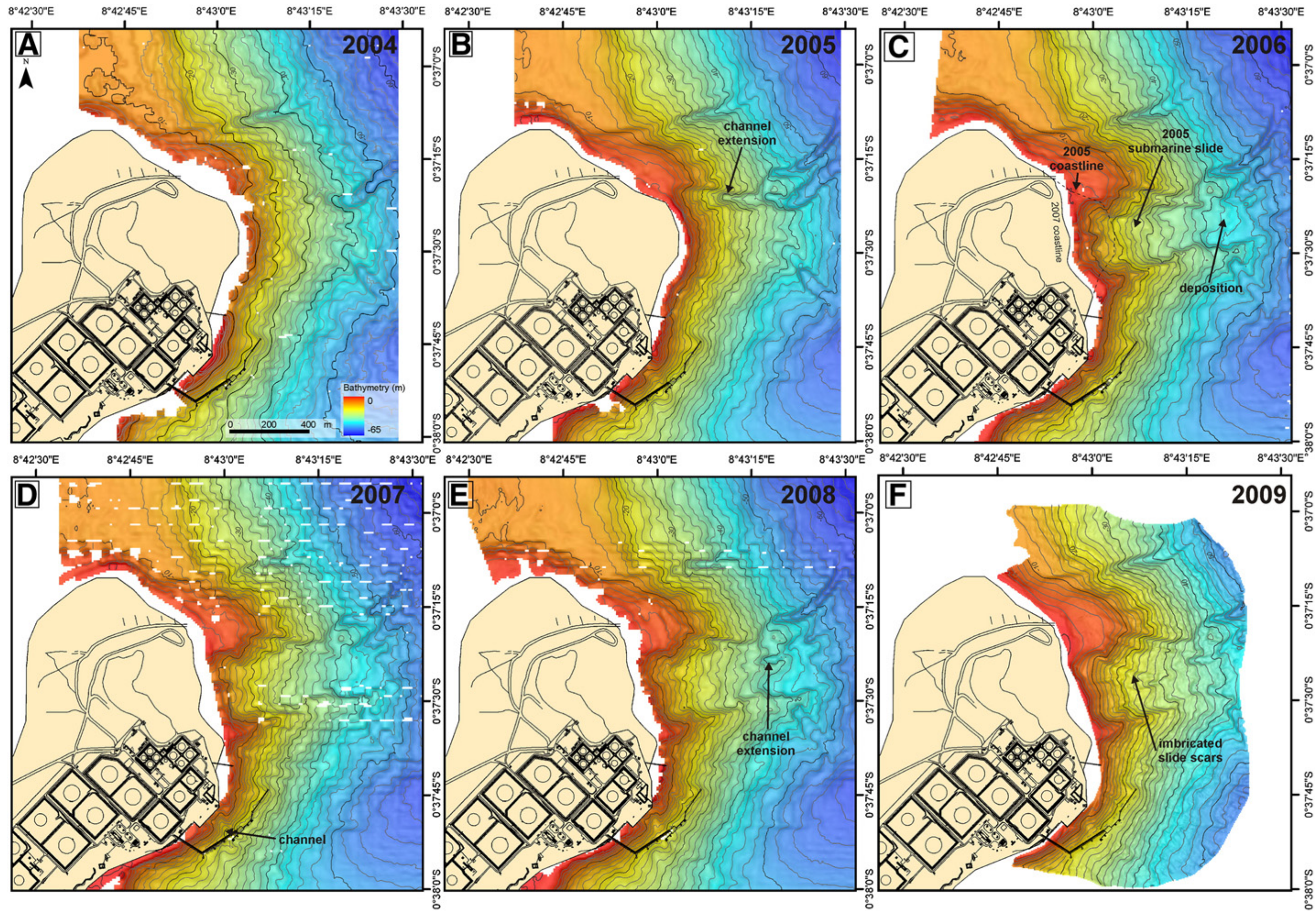

Fig. 2. Annual bathymetric maps offshore Pointe Odden (IOTA SURVEY) — A: 2004; B: 2005; C: 2006; D: 2007; E: 2008; F: 2009.

The 2006 bathymetry dataset shows the slide geometry at most within 8 months after the event occurred, allowing a realistic estimation of the eroded sediment volume involved in the slide. Depth differences calculated from DEM subtraction show enhanced erosion patterns close to the coast (up to 23 m, Fig. 3B). The apparent slide volume (SVa; Smith et al., 2007), corresponding to the slide volume based upon the 2005–2006 DEM subtraction, is estimated at 2,460,000 m^3 over an area of 290,000 m^2. This estimate takes into account the submarine portion of the slide (2,290,000 $m^3 \pm$ 100,000 m^3) and the subaerial portion of the sand bank, resulting in a significant landward migration of the coastline of ca. 230 m (Fig. 3B). Considering a mean elevation of 2 m of the coast (IOTA SURVEY, 2006), the eroded subaerial portion of the sand bank (85,000 m^2) may be estimated at ~170,000 m^3.

4.1.4. Slide scar infill

Analysis of the 2006–2008 DEM indicates that the slide scar infill occurs by migration of deposits inside the depression. Initial deposition during the post-failure stage occurs essentially on the north side and headwalls of the slide scar due to its proximity to the source of sediment supply (Fig. 3C). Between 2006 and 2007, around 120,000 ± 20,000 m^3 of sediment are deposited between 15 m and 35 m water depth, which is equivalent to an average sedimentation rate of ~1.5 m over an area of 50,000 m^2 (Fig. 3C). Once this area is partially filled, the deposits successively migrate southward (~120,000 ± 30,000 m^3, Fig. 3D) and then eastward (not shown) to fill other areas of bathymetric lows. Therefore, the infill of the scar does not occur homogeneously throughout the depression but by compensation until its complete infill.

Concerning the morphological evolution of the depression, the specific sediment budget of the slide scar has been evaluated for the 2005–2006 and 2005–2008 periods. To compare these two estimates, we focused on the 2005–2008 slide scar extent, which is slightly lower compared to the real dimensions of the slide scar. The apparent slide volume (Smith et al., 2007) between 2005 and 2006 is estimated at 2,260,000 ± 100,000 m^3 over an area of 270,000 m^2, which corresponds to an average depth increase of approximately 8.4 m. In contrast, the apparent slide volume between 2005 and 2008 is estimated at 1,930,000 ± 100,000 m^3, reflecting an average depth increase of 7.1 m. From these estimates, a filling rate of ~160,000 m^3/yr may be proposed. Assuming a constant deposition rate, the 2005 slide scar would be filled within 14 years. The same calculations performed with an average deposition rate of ~120,000 m^3/yr (volume of the depositional units in the slide scar between 2006 and 2008) suggest a total infill of the slide scar within 19 years.

4.1.5. Sedimentary budget

Annual erosion rate offshore Pointe Odden ranges between 310,000 ± 210,000 m^3 and 2,660,000 ± 450,000 m^3 while sedimentation rate is estimated between 150,000 ± 120,000 m^3 and 570,000 ± 300,000 m^3 (Fig. 3F). Due to few bathymetric surveys and recurrent erosional phenomena during the period of study, it is difficult to estimate a truly representative sediment budget. However, a first estimate may be proposed using the average volume of deposited and eroded sediment during the year 2007–2008, which is the most significant period of natural sediment accumulation along the coastline (Fig. 3D). If we consider an average annual erosion rate of ~350,000 m^3/yr and a sedimentation rate of

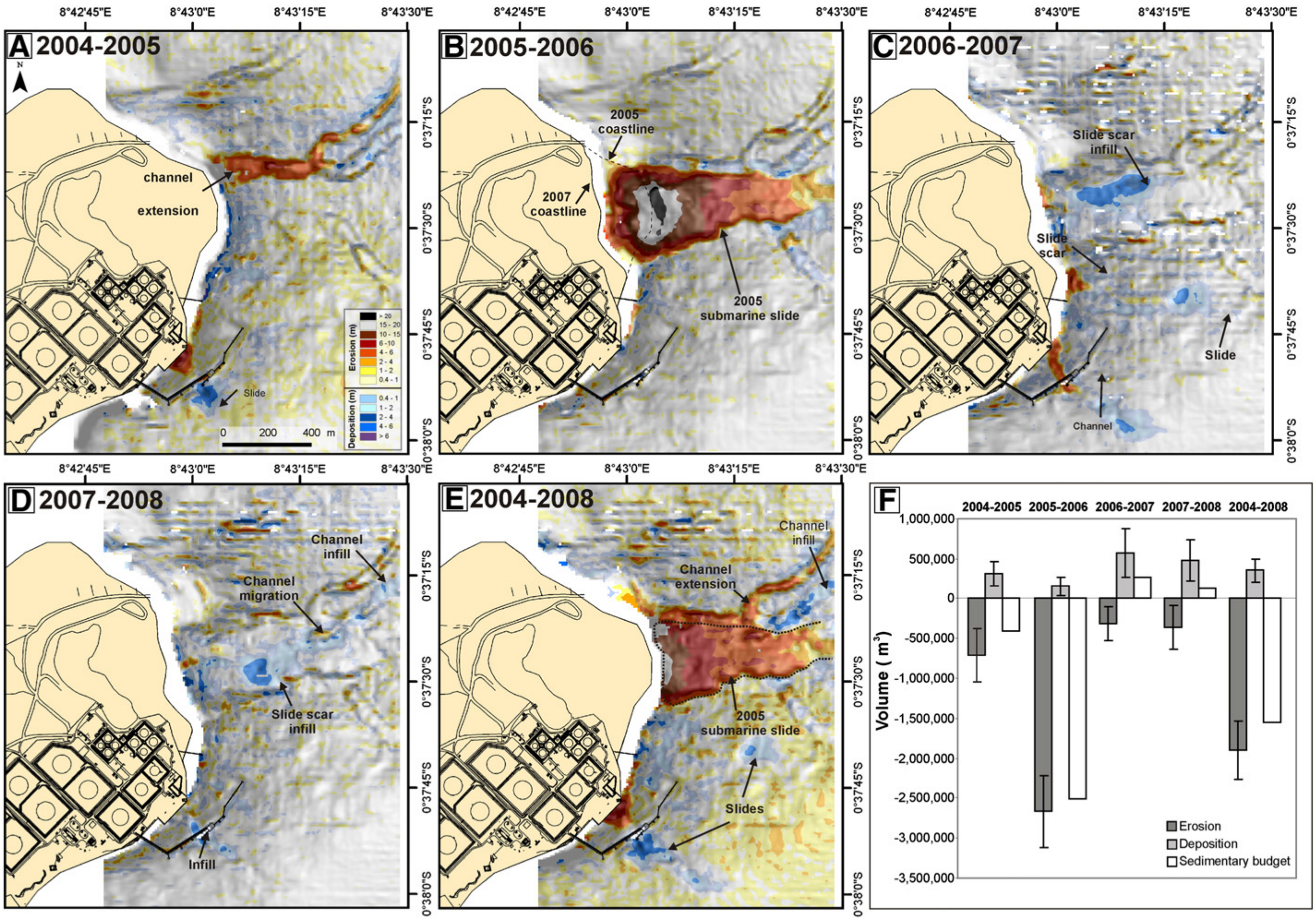

Fig. 3. Depth differences calculated through DEM subtraction between 2004 and 2008 and their associated sedimentary budgets. A: 2004–2005; B: 2005–2006; C: 2006–2007; D: 2007–2008; E: 2004–2008; F: Synthetic chart representing the eroded and deposited volume of sediment with interpolation error for each successive year and their associated sedimentary budget.

~500,000 m^3/yr, Pointe Odden sediment budget would reach around 150,000 m^3/yr. Sedimentation rates obtained from these calculations are slightly higher than the sedimentary transport (300,000–400,000 m^3) proposed by Bourgoin et al. (1963). However, due to the large interpolation error associated to the estimate, these results should be treated with care.

At a pluri-annual scale (2004–2008), Pointe Odden area lost ~$1,900,000 \pm 420,000$ m^3 of sediment, while local accumulation is estimated at ~$350,000 \pm 160,000$ m^3 over an area of 1.95 km^2 (Fig. 3F). The erosion caused by the 2005 submarine slide represents about 80% of the eroded sediment volume during these 5 years (Fig. 3E). The channel extension in the slide scar region is also observed (Figs. 2B and 3A). Finally, a large area of moderate erosion (0.4 m–1.5 m) is visible on the DEM subtraction (Fig. 3E). Only the multi-annual comparison of the bathymetric data allowed us to highlight the existence of this small but constant annual erosion in the study area. Depositional areas offshore Pointe Odden are mainly localized around the coast and in the vicinity of Chalands Bank (Fig. 3E).

The comparison of calculated annual cumulative (−2,520,000 m^3) and four-year average (−1,550,000 m^3) reveals that the mean sediment budget obtained on a pluri-annual scale is underestimated at about 40% compared to the annual cumulative sediment budget on the same period. This observation highlights that the use of averaged data over periods of several years underestimates the real sediment budget due to the intense morphological evolution at annual scale.

4.2. Sedimentological and geotechnical characterization of the area

Based on the CPTU measurements and punctual sedimentological analyses (Delft, 1984), three main sedimentary units were identified from top to bottom (Fig. 4).

Unit A consists of 1 m of fine to medium brown-yellow, well-sorted sand (Median (Md): 250 μm, Trask Sorting Index (So): 1.35), interpreted as sediments deposited by longshore drift (Le Fournier, 1973; Delft, 1984). qt is higher than 20 MPa and porosity ranges from 34 to 49%.

Unit B is constituted of 16 m of fine to medium sand with silty-sand intervals between 10 and 12 m depth below seafloor (dbsf). Sedimentological analyses indicate that this unit is principally characterized by well-sorted massive sand (Md: 180–260 μm; So: 1.35–1.5) containing shell fragments and organic material (Delft, 1984). Sedimentary structures such as planar and convolute laminations are present. This sedimentary unit is interpreted as being the result of gravitary flow deposition (Le Fournier, 1973; Delft, 1984). Unit B shows large qt variations: between 10 and 12 m dbsf, values of qt are low (5–15 MPa). Samples collected in these levels correspond to grey silty-sand of high porosity (up to 51%) compared to the saturated critical porosity (48.7%; Delft, 1984). Between 5 and 10 m or 12 and 17 m dbsf, qt increases up to 25 MPa and porosity slightly decreases (down to 48%).

Unit C consists of approximately 10 m of alternating sand and silty sand. In general, this unit shows high qt values (locally more

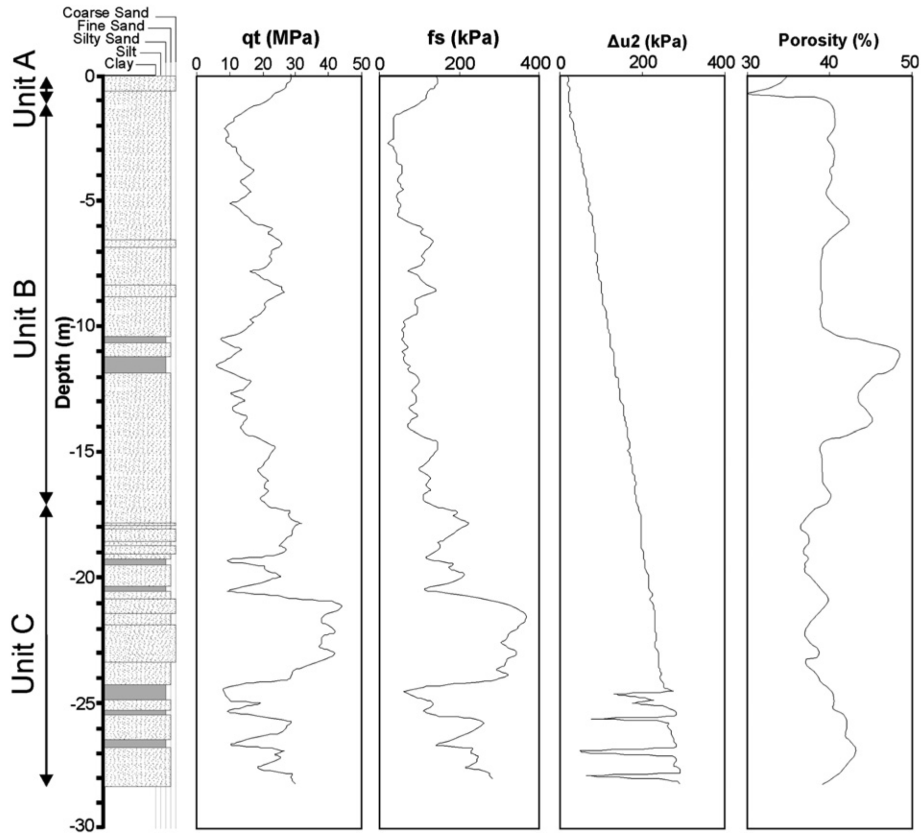

Fig. 4. Geotechnical characterization of PO borehole (see location on Fig. 1B): Lithological log based on the SBTn Index (Robertson, 1990); tip resistance (qt, MPa); sleeve friction (fs, kPa), excess pore pressure (Δu2, kPa) and porosity (%).

than 40 MPa) and relatively low porosity values (between 34 and 49%). However, interlayered metre-thick beds of low qt (10–15 MPa) are encountered at around 20 m and 25 m dbsf. Due to the lack of core material, no sedimentological analyses were performed in this unit.

5. Discussion

5.1. Channel formation and sedimentary processes

Interpretation of bathymetric data suggests active retrogressive erosion in areas of critical stability. Because of failures occurring at the slope toe, sediment located upslope becomes prone to failure (Farre et al., 1983). Erosion then propagates upslope under the form of successive slide scars (Fig. 2F) or through headward enlargement and entrenchment of existing channels (Fig. 3A). The most striking feature is that this process can generate large volumes of eroded sediment on a very short-time scale (up to 170,000 m^3 in 1 year, Fig. 3A). The presence of successive slide scars along the slope (Fig. 2F) suggests that retrogressive erosion due to sediment failures occurs in this area. However, it is not clear if a substantial part of repeated erosion may be also related to downslope sediment flows that progressively oversteepen the seafloor and trigger retrogressive erosion (Pratson et al., 1994; Pratson and Coakley, 1996). Gravitary flows initiated upslope would be preferentially oriented through these existing bathymetric lows and would contribute to local erosion, leading to the formation and upslope propagation of a relatively straight channel with steep-walls. Once the channel head reaches the water depth under which longshore drift is active, it receives a more constant sediment supply leading to increased downward erosion and enhanced channel incision by gravitary flows.

5.2. Mass wasting processes

The combination of high-resolution bathymetric data prior to and after the 2005 submarine slide provides an exceptional opportunity to reconstruct its evolution.

5.2.1. Conditions prior to failure

An average net sediment budget of ~150,000 m^3/yr was estimated from the comparison of bathymetric data, explaining the constant seaward migration of the coastline via sediment accumulation. This estimate is confirmed by extensive deposition (60,000 ± 20,000 m^3) along the portion of the coast subsequently affected by the slide (Fig. 3A). The average slope angle measured 5 months before the 2005 event was in the range of 8° between 0 and 10 m water depth (100 m offshore) with a gradual decrease to about 3° at 30 m water depth (300 m offshore). Enhanced lateral erosion between 2004 and 2005 leading to the landward migration of a channel close to the present slide scar (Fig. 3A), confirms that the area was previously subject to small-scale slope instabilities.

5.2.2. Failure mechanisms

5.2.2.1. Susceptibility factors promoting failure

The steep slopes at shallow water depths (8° between 0 and 10 m water depth) observed 5 months prior to the slide event suggest the influence of oversteepening on slope-failure initiation. This observation is in agreement with the work of Lacasse and Boisard (1996) which demonstrated that a gradient of 8–9° was the critical slope angle in the initiation of large mass wasting events on Pointe Odden.

Sedimentological characteristics of deposited sediments on Pointe Odden also suggest that they are prone to failure. Sediments are mainly composed of fine to medium, well-sorted (1.35 < So < 1.5) sand. The uniform grain size distribution observed in the samples facilitates flow sliding (Kramer, 1988). High porosity and corresponding low qt values in the studied samples are preferentially observed in laminated and convoluted thick sandy beds (Le Fournier, 1973). The qt variations measured in Unit B and occasionally Unit C may correspond to an alternation of easily drainable massive sand beds and less permeable convoluted sandy beds. In-situ salinity measurements in a borehole located on the coast 120 m from the PO site show low salinity values (0.5–1.7 g/L) in buried layers and higher values in superficial layers (2.5–10 g/L; Delft, 1972) confirming that permeability barriers may be present.

These observations are consistent with the hypothesis of liquefaction processes offshore Pointe Oden. Liquefaction flow slides are recurrent phenomena in coastal and deltaic deposits (Sladen et al., 1985; Kramer, 1988; Christian et al., 1997; L'Heureux et al., 2010). The liquefaction process is generated when the excess pore pressure in sandy sediments balances the initial vertical effective stress, leading to a sudden behaviour change of the sediment from solid to liquid (Terzaghi and Peck, 1967). Liquefiable material is usually poorly packed and highly-porous, allowing high water content and relatively low density sediments to eventually fail when an external stress is added. Such a stress can be the result of dynamic effects produced by earthquakes, surface waves or to static effects produced by tidal variations, sediment piling and shear state of sand at critical density state (Chillarige et al., 1997). The good agreement between the thickness of the eroded sediment and the depth of highly porous sandy layers in the borehole site (−10 m) suggests that these weak layers may form a preferential slip plane for the failure. Even if the geotechnical data do not permit to completely banish the role of sensitive clay in the occurrence of the 2005 slide, the existence of such loose sandy intervals more likely appears to be at the origin of the event.

5.2.2.2. Possible triggering mechanisms

Different environmental processes such as exceptional meteorological conditions, cyclic loading, rapid sedimentation or dredging operations may trigger or contribute to the initiation of mass wasting in sensitive coastal areas.

Particularly intense meteorological or oceanographic conditions may trigger submarine mass wasting. Exceptionally heavy rainfall before the 1979 Nice harbour disaster accelerated the seepage of fresh water and the decrease of the effective stress of the sensitive clay layer which lead to slope failure (Dan et al., 2007). Moreover, high swell conditions can generate significant dynamic pressures on the seafloor, inducing pore water pressure fluctuations within the seabed (Jeng, 2001) and liquefaction of soils (Dalrymple, 1979). Transient changes in pore water pressure associated with high swell conditions have been suggested as a triggering mechanism for slope failures and gravitary flows (Paull et al., 2003; Xu et al., 2004). However, neither significant precipitation rates (<5 mm/h; http://www.sat-ocean.com/squalls.html) nor exceptionally high surf conditions susceptible to generate excess pore pressure were recorded between June and July 2005 in Port-Gentil area. Moreover, considering the absence of the precise date of the event, it appears difficult to involve tidal variations as a triggering mechanism.

Cyclic loading may also induce excess pore pressure and conducts to liquefaction processes. Earthquake data along the Gabonese margin were collected from the United States Geological Survey database (http://earthquake.usgs.gov). No significant earthquakes were recorded during the year 2005, suggesting that seismic loading cannot be considered as a triggering mechanism. Moreover, no pile installations susceptible to generate vibrations were reported before the event.

Static loading may result from dredging operations or longshore drift sedimentation. To our knowledge, no dumping/dredging operations were performed during the period of study. Frequent dredging operations on the Chalands bank were performed until the year 1993 (Lateux, 2007). Since this year, the abandonment of dredging operations suggests that the erosive structures observed in 2004–2005 and 2006–2007 have a natural origin rather than anthropogenic. Indeed, the orientation change of the coast in the area of Pointe Odden conduces to a sharp decrease of the intensity of longshore drift and contributes to high sedimentation rates. Sediment accumulation may generate excess pore pressure in underlying layers which dissipates at a rate depending on the degree of accumulation and permeability of the sediment. Shear stress related to sediment load on loose layers may conduce to overpressure development in the pores and generates liquefaction processes. Even if the triggering mechanism of the 2005 slide remains still uncertain, our results suggest that shear stress associated to sediment overloading and slope oversteepening would be an important mechanism.

6. Conclusions

This contribution presents the first detailed study of submarine slide initiation and evolution using recurrent bathymetric analysis. The comparison of annual bathymetric data highlights the constant sediment load and deposition along the coast of Pointe Odden by longshore drift, resulting in high sediment accumulation at shallow water depth. Because of sediment overloading and slope oversteepening, small-scale instabilities are generated (successive slide scars, channel formation and growth by retrogressive erosion). However, when stability becomes critical, large failures occur (e.g. 2005 submarine slide). Geotechnical measurements and sedimentological analyses on the study area suggest that flow liquefaction would be at the origin of the 2005 event. Even if the triggering mechanisms of the 2005 slide remain still uncertain, shearing of loose sandy layers related to both sediment overloading and slope oversteepening seems to be the most probable triggering mechanism of the event.

Since the 2005 slide, substantial morphologic changes are observed, indicating that the slide scar is currently experiencing an infilling stage. This infill does not occur homogeneously throughout the depression but via migrating deposits that progressively fill the slide scar by compensation. Assuming a constant deposition rate, the total infill of the slide scar would occur between 14 and 19 years. These results suggest that 1) slide scars may evolve quickly through time, by enlargement or filling processes; 2) they can disappear rapidly from seafloor morphology and 3) Pointe Odden area could once again be in a state of critical stability from 2020 onwards.

Overall, this study confirms that monitoring of sensitive areas with high-resolution bathymetric tools brings new elements on the understanding of submarine mass failure mechanisms and their development. Comparison of bathymetric data forms a preliminary source of information for anticipating potential damages to both coastal areas and offshore infrastructures.

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