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Fluid flow regimes and growth of a giant pockmark

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Abstract:

Pockmarks are seafloor depressions commonly associated with fluid escape from the seabed and are believed to contribute noticeably to the transfer of methane into the ocean and ultimately into the atmosphere. They occur in many different areas and geological contexts, and vary greatly in size and shape. Nevertheless, the mechanisms of pockmark growth are still largely unclear. Still, seabed methane emissions contribute to the global carbon budget, and understanding such processes is critical to constrain future quantifications of seabed methane release at local and global scales. The giant Regab pockmark (9°42.6′ E, 5°47.8′ S), located at 3160 m water depth near the Congo deep-sea channel (offshore southwestern Africa), was investigated with state-of-the-art mapping devices mounted on IFREMER's (French Research Institute for Exploitation of the Sea) remotely operated vehicle (ROV) *Victor 6000*. ROV-borne micro-bathymetry and backscatter data of the entire structure, a high-resolution photo-mosaic covering 105,000 m^2 of the most active area, sidescan mapping of gas emissions, and maps of faunal distribution as well as of carbonate crust occurrence are combined to provide an unprecedented detailed view of a giant pockmark. All data sets suggest that the pockmark is composed of two very distinctive zones in terms of seepage intensity. We postulate that these zones are the surface expression of two fluid flow regimes in the subsurface: focused flow through a fractured medium and diffuse flow through a porous medium. We conclude that the growth of giant pockmarks is controlled by self-sealing processes and lateral spreading of rising fluids. In particular, partial redirection of fluids through fractures in the sediments can drive the pockmark growth in preferential directions.

1. Introduction

Pockmarks are seafloor depressions considered to be the surficial expressions of fluid seepage processes, as well as mud volcanoes or gas hydrate pingoes (Judd and Hovland, 2007; Serié et al., 2012). However, pockmark morphologies, sizes and densities vary greatly, suggesting that the term "pockmark" is loosely constrained and applies to a broad range of seafloor features (King and MacLean, 1970; Hovland et al., 2002; Judd and Hovland, 2007; Gay et al., 2007).

The shape of a pockmark is the result of local conditions and the processes involved in the formation and growth of pockmarks are likely to vary between settings. Several formation mechanisms have been proposed that involve either slow and continuous processes (Hovland et al., 1984; Harrington, 1985; Sultan et al., 2010) or more rapid and sudden events (MacDonald et al., 1994; Hovland et al., 2005). All the different hypotheses confirm that several processes could apply and that the main

mechanisms involved in the formation and growth of pockmarks remain largely unclear. A better knowledge of these processes is crucial to strengthen our understanding of the dynamics of methane release from the seabed into the ocean.

In this study we present for the first time the results of high-resolution acoustic and optical surveys of the giant Regab pockmark in the lower Congo basin. Surveys were conducted using the Ifremer's remotely operated vehicle (ROV) Victor 6000 during the West African Cold Seeps (WACS) cruise on the RV Pourquoi Pas? in January-February 2011. The data set is fully

comprehensive and includes in particular ROV-borne micro-bathymetry and backscatter maps of the entire pockmark together with detailed sidescan-based mapping of seafloor gas emissions. This is completed by a 105,000 m^2-large high-resolution photo-mosaic and fauna mapping of the most populated and active area of the pockmark in terms of seepage intensity.

To date, such a comprehensive data set of a pockmark feature is unique and gives unprecedented insights on the detailed morphology of complex pockmarks. In particular, the results provide valuable clues to decipher the functioning of giant pockmarks, which are discussed in this study.

STUDY AREA

The Regab pockmark is located on the Gabon-Congo-Angola margin ~10 km north of the Congo channel at ~3160 m water depth (Ondréas et al., 2005). In this area, muddy hemipelagic sediments cover turbiditic channel/levee bodies of the Congo fan (Droz et al., 1996; Gay et al., 2003). Seismic data show that the pockmark is linked to a deep palaeochannel/levee system that could act as reservoir for the seeping fluids. Advecting fluids are enriched in methane of biogenic origin (Charlou et al., 2004) and sustain an abundant population of chemosynthetic fauna (Olu-Le Roy et al., 2007) within the pockmark. Crusts of authigenic carbonates are extensive (Ondréas et al., 2005; Pierre and Fouquet, 2007) and widespread presence of shallow gas hydrates was inferred from seafloor observations and sediment cores (Charlou et al., 2004; Olu-Le Roy et al., 2007; Pierre et al., 2012).

DATA AND METHODS

Bathymetry data were acquired with a multibeam echosounder (MBES) Reson Seabat 7125 running at 400 kHz. The main survey was conducted from 30 m altitude over a 1.2 km^2-large area and allowed to map the entire pockmark. An additional survey was conducted from 8

m altitude over a 0.175 km^2-large subarea of the pockmark. The data was processed with CARAIBES (Le Gal and Edy, 1997) and the final bathymetry and backscatter maps include both data sets with a 25 cm resolution.

Imagery data were acquired simultaneously to the second bathymetry survey with the Victor 6000's high sensitivity OTUS photo-camera, and the photomosaic was constructed using the ROV navigation with LAPM Tool (Marcon et al., 2013a). Therefore, an excellent match of the photomosaic onto the bathymetry was obtained. The mosaic was used to map the carbonate precipitates and the fauna distribution. Mapped fauna include siboglinid polychaetes (tubeworms), bathymodiolid mussels and vesicomyid clams.

Seabed gas emissions in the water column were mapped using the CARIS program to visualize the sidescan data. Sidescan data allowed us to identify the presence of gas in the water column as far as 30 m on each side of the ROV. Due to the dense track line spacing, 86% of the pockmark was mapped. Finally, the presence of gas emissions and outcropping hydrates on the seafloor was confirmed using dive videos.

RESULTS

Bathymetry

The bathymetry (Fig. 1) shows that the pockmark is a large elliptical structure with diameters ranging between 700 and 950 m. It stretches in the N70 direction along an elongated feature, possibly related to a fracture. Elongated appendices can be observed in several places at the edge of the pockmark. The largest of these occur in the northeastern side and seem to be extensions of the N70 fracture expression. The pockmark boundary shows a sharp edge in the northeastern half, and becomes softer toward the southwestern side. The bathymetry also reveals

that Regab is composed of numerous (>1000) rounded depressions, or sub-pockmarks, of various sizes (from less than 5 m to 100 m in diameter) and depths (from 0.5 to 15 m).

Those depressions are not randomly distributed and two zones can be clearly distinguished (Fig. 1): zone 1 is composed of relatively large (>20 m) and deep (>3 m) sub-pockmarks, and is characterized by a very rugged surface and the presence of carbonate elevations and slabs; zone 2 has a smoother appearance but is scattered by more than a thousand very small (<5 m) to medium-sized (up to 60 m) and shallow (<3 m) pits, also known as unit pockmarks.

Backscatter and Gas Plumes

The signal reflectivity and gas plume distribution show a very characteristic pattern over the pockmark area (Fig. 1). Zone 1 is almost entirely characterized by high-backscatter reflectivity areas. The largest of them is located around the N70 longitudinal feature identified on the bathymetry; it stretches up to and along the eastern edge of Regab. Two additional areas of high backscatter occur precisely on the boundary of the pockmark, respectively on the northern and southern edges; they are associated with distinct and relatively large sub-pockmarks (80–100 m in diameter). Zone 2 has a comparatively low-backscatter signature, but is scattered by a myriad of high-reflectivity anomalies of various sizes (up to 50 m in width) and shapes; these anomalies are consistently located within the numerous shallow unit pockmarks identified from the bathymetry. Vice versa, zone 2 unit pockmarks are always associated with high-reflectivity anomalies. Gas emissions occurred exclusively within the largest high-reflectivity area of zone 1.

OTUS and Video Imagery

The faunal and carbonate mapping from the photomosaic reveals a clear segregation between zones 1 and 2, and a clear causal link with backscatter data (Fig. 2).

The rugged morphology of zone 1 is shaped by massive carbonate crusts that form thick elevations around sediment-covered depressions. Gas hydrates occur at the surface in several places (Fig. 1) under carbonate crusts. Near the most active areas in terms of gas emissions, carbonate elevations host abundant mussel and tubeworm populations (Fig. 1–2). Generally, mussel beds are located closer to active gas emissions and in areas of disturbed seafloor, where carbonate crusts seem broken or displaced. Clams are generally distributed in sediment-covered areas of negative relief, but rarely within the deepest depressions of zone 1. Conversely, carbonate crusts, mussels and tubeworms are never observed in zone 2, and the imagery data (photomosaic + dive videos) only reveals soft sediments and clams presence. However, the clam distribution in zone 2 is very distinctive and shows that clams are only present in the center of the unit pockmarks, precisely where the zone 2 high reflectivity anomalies occur (Fig. 2).

DISCUSSION

Previous studies showed that the activity at Regab is linked to the presence of a vertical chimney under the pockmark that is rooted into a palaeo-channel (Ondréas et al., 2005; Gay et al., 2006b) and that the advection of fluid through the gas hydrate stability zone is possibly related to a fault (Gay et al., 2006a). Such interpretation is supported by the elliptical shape of the pockmark and the linear feature evidenced from the bathymetry (Fig. 1). However, although a fracture is likely the main feature controlling the fluid expulsion pattern at Regab, the new high-resolution data revealed two very distinctive zones within the pockmark. These two zones show striking differences and are clearly the expressions of very distinct fluid flow regimes and formation mechanisms.

Zone 1: Intense and Focused Fluid Flow

Thick carbonate elevations, rich fauna and intense gas venting are clear indications for high, focused and long-term seepage activity. First, the abundance of thick crusts of authigenic carbonates at the surface suggests that the anaerobic oxidation of methane (AOM) occurs close to the sediment surface (Aloisi et al., 2002) and has been active for a long period of time (Luff and Wallmann, 2003). A shallow AOM front would therefore indicate an intense upward flux of methane from below (Borowski et al., 1999). Next, patterns in the distribution of mussels and tubeworms (Olu-Le Roy et al., 2007 and Figure 2b-c) indicate that the chemical fluxes are heterogeneous across the zone. In particular, mussels and gas emissions were often observed together. Marcon et al. (2013b) showed that mussel occurrence at Regab reflect areas of intense fluid flow, where chemical supply is locally high. Finally, the faunal distribution (Ondréas et al., 2005), the backscatter signal and the overall shape of zone 1 show a strong correlation with the N70 axis identified from the bathymetry. It is likely that such discontinuity provides the main pathways for focused fluid flow in this zone.

The formation of zone 1 topography is not yet fully understood but seafloor observations showed that gas emissions and outcropping hydrates occur in areas of broken crusts or of displaced blocs; such features are evidence for catastrophic events, and are likely related to sudden release of pressured free gas from under the crusts (Hovland et al., 2005) and to rafting of gas hydrates deposits (MacDonald et al., 1994).

Zone 2: Diffuse and Homogeneous Fluid Flow

Carbonates, gas escape and hard substratum fauna were not observed in zone 2. Instead, hundreds of small and medium shallow sub-pockmarks populated by clams scatter the zone (Fig. 1–2). We postulate that the relatively smooth surface of zone 2 is the expression of a more diffuse and uniform fluid flow pattern than in zone 1. This is supported by previous works in the

Congo basin that correlated the distribution of clams to transient and low seepage activity areas (Olu-Le Roy et al., 2007; Sahling et al., 2008; Marcon et al., 2013b).

The formation of those sub-pockmarks could be related to various mechanisms such as: sediment lifting by ascending gas (Hovland et al., 1984), pore fluid drainage (Harrington, 1985; Hovland et al., 2010), rafting of hydrate clumps (MacDonald et al., 1994), or hydrate dissolution (Sultan et al., 2010). A mechanism involving free gas escape in this zone is, however, not supported by the gas emission mapping. In addition, mechanisms involving the presence of shallow gas hydrate deposits are not supported by backscatter data and the observed scarcity of faunal communities (Fig. 1–2), which suggests low seepage activity. However, pore fluid advection does occur at Regab, with rates up to 2.3 mm/a at the western edge of the pockmark (Chaduteau et al., 2009). This favors the models by Harrington (1985) and Hovland et al. (2010), according to which advecting pore water is retained in fine sediments until it is released due to water or gas-triggered pressure buildup. Subsequent sediment winnowing and water drainage ultimately leads to the formation of pits, or unit pockmarks, at the surface.

Possible Mechanisms Controlling the Pockmark Growth

We propose that self-sealing processes and subsequent fluid flow redirection control the pockmark growth (Fig. 3). By causing sediment permeability to decrease, the formation of authigenic carbonates may ultimately form a natural seal for rising fluids (Hovland, 2002). Assuming non-decreasing seepage intensity, a pore-pressure increase would lead excess fluids to spread laterally until sufficient pathways to the sediment surface become available and that uniform flow at hydrostatic pressure is restored. This is similar to the concept of ‘shortest and most permeable vertical pathway’ used to explain the migration of petroleum fluids in rocks and sediments (Mackenzie and Quigley, 1988; Floodgate and Judd, 1992).

Redirected fluids may transit as diffuse flow through non-fractured porous sediments or as focused flow along sediment discontinuities. Regab provides evidences for both: mainly focused flow in zone 1 and diffuse flow in zone 2. Results suggest that rising fluids in zone 1 were partly redirected through fractures or discontinuities within the sediments, thus leading the pockmark growth into the N70 preferential direction. In the absence of similar preferential fluid pathways, fluid flow in zone 2 spreads over a relatively large area and reaches the surface in a more isotropic way and with a lower intensity than in zone 1.

CONCLUSION

This is the first study to present such a high resolution and comprehensive mapping data set of an entire giant complex pockmark. It demonstrates that current modern techniques exist that allow for detailed and large-scale investigations of the deep-seafloor. The value of such comprehensive data sets goes beyond the mere production of high quality maps. By giving full sight of the area of study it allows getting a deeper understanding of the system and the long-term processes involved. In this study, it allowed identifying zones with distinct fluid flow regimes, and constraining growth mechanisms for giant pockmarks. These findings on pockmark dynamics constitute a base model to orientate future work and constrain assessments of seabed methane fluxes at giant pockmarks.

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FIGURE CAPTIONS

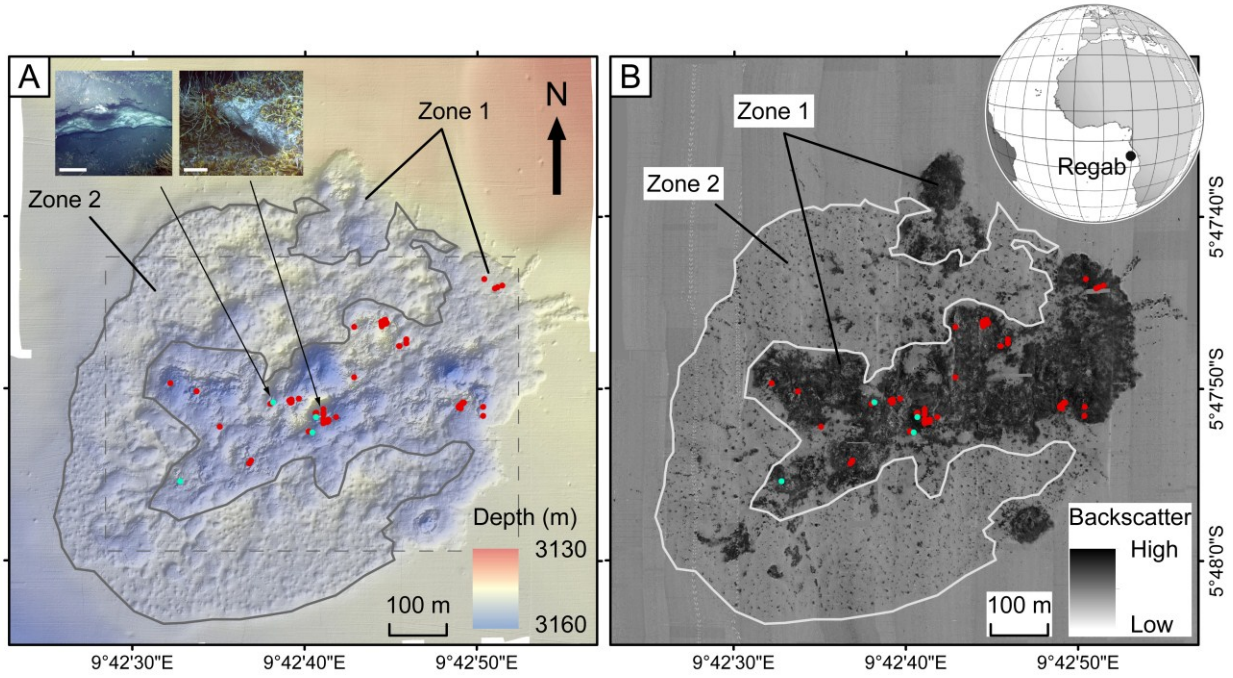

Figure 1. (A) Micro-bathymetry and (B) backscatter intensity of the Regab pockmark. Seabed gas emissions (red dots) were identified from both sidescan and video data. Gas hydrate outcrops (blue dots) were identified from video data only. The globe view shows the location of the Regab pockmark. The image insets show hydrate outcrops under broken/tilted carbonate blocks, mussels and tubeworms (scale bar represents 50 cm). Zone 1 is characterized by a rugged surface with large (>20 m) and deep (>3 m) depressions, strong backscatter signature, gas emissions and gas hydrates at outcrop; zone 2 has a smoother appearance with comparatively low backscatter signature; it is scattered by numerous (>1000) shallow (<3 m) depressions, however, gas emission sites and hydrate outcrops have not been observed. The dashed rectangle in A shows the extent of Figure 2.

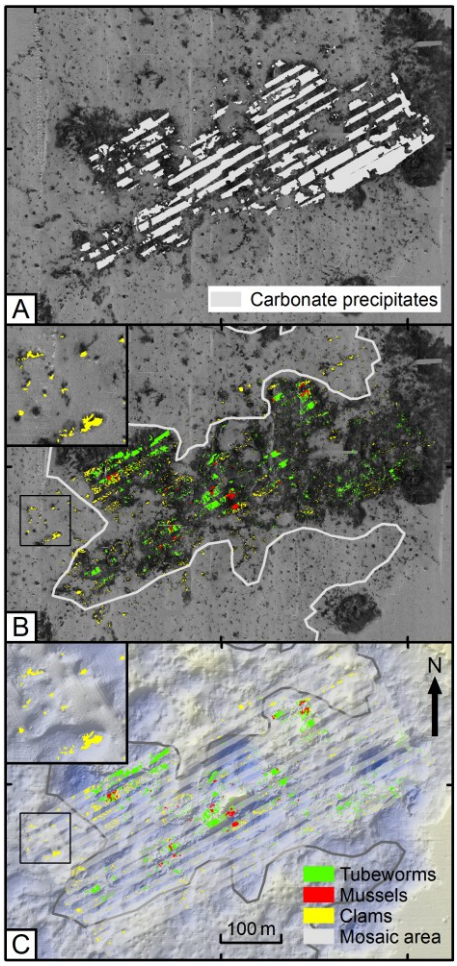

Figure 2. A: Carbonate distribution and backscatter in the center of Regab; the carbonate precipitates cause most high-backscatter anomalies. B: Fauna distribution and backscatter; tubeworms and mussels occur in areas where high-backscatter is caused by carbonate precipitates; clam shells generate high-backscatter anomalies unrelated to precipitates. C: Fauna distribution and micro-bathymetry; tubeworms and mussels occur mainly on elevated areas; clams are present in lower areas, but rarely in the deepest depressions. B and C: Inserts represent magnifications of the same area (black rectangles) of zone 2. The mosaic was constructed with the LAPM tool (Marcon et al., 2013a) by geo-referencing individual images with the ROV navigation data.

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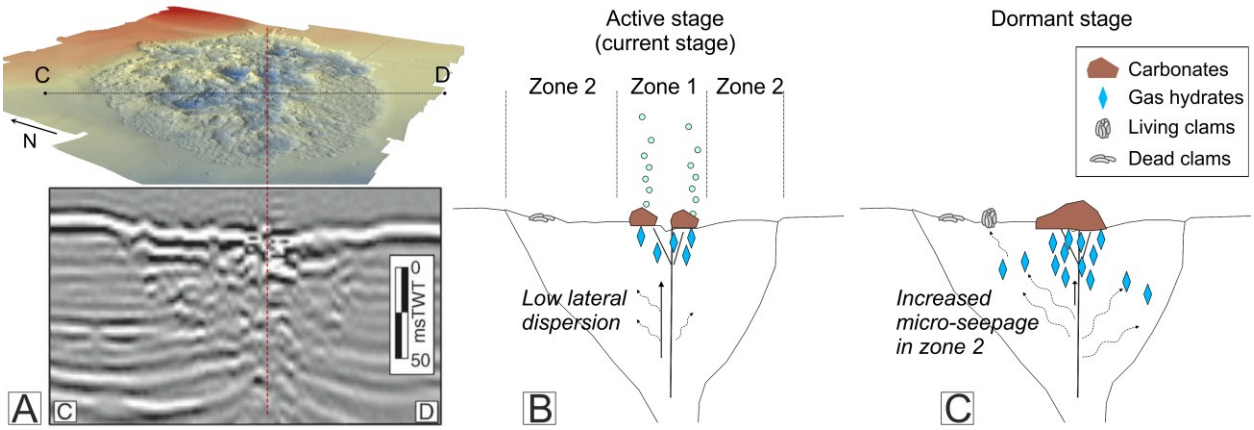

Figure 3. Plumbing system of Regab. A: The surficial fracture expression of zone 1 is located right above the main seismic chimney. B: Schematic of Regab in its current active stage; seepage is driven along focused pathways, leading to carbonate formation, shallow hydrates, gas escape and abundant fauna in zone 1. C: Given time, carbonates and hydrate deposits cause sediment vertical permeability to decrease and rising fluids to redirect and spread within surrounding sediments. Seismic data after Gay et al. (2006b).