

Carbonate mounds in a mud volcano province off north-west Morocco: Key to processes and controls

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Abstract

This paper presents a new cluster of carbonate mounds discovered in 2002 in the Gulf of Cadiz off Morocco (*R/V Belgica* 2002) in water depths of 500 to 600 m amidst a field of giant mud volcanoes. Multibeam bathymetry, side scan sonar imagery and 2D seismics are analyzed to present four mound provinces: (1) the Pen Duick Mound Province on the Pen Duick Escarpment, (2) the Renard Mound Province on the Renard Ridge, (3) the Vernadsky Mound Province on the Vernadsky Ridge and the Al Idrisi Mound Province on the gas-blanked sediments above the buried Al Idrisi Ridge. Video imagery and surface samples are described to ground-truth the different mound areas.

The paradox is that nearly no live corals are presently being observed at the surface of the mounds, while the mound cores display throughout a high number of reef-forming cold-water coral fragments (scleractinians) in association with numerous associated fauna formerly inhabiting the econiches provided by the coral framework. Environmental and oceanographic conditions during the recent past (glacials/stadials) were probably more favourable for cold-water coral growth.

Pore water analyses in on-mound cores at the south-eastern edge of Pen Duick Escarpment give evidence of focused, higher methane fluxes and sulphate reduction rates on mounds than in the surrounding sediments. Cores from several mounds display horizons of strong corrosion and dissolution of the coral fragments.

A three-phase model for carbonate mound evolution in these settings is proposed. (1) In a first stage external controls (positive oceanographic and environmental conditions, the presence of an active planktonic food chain, based on a high primary production, and a suitable substrate) are responsible for the initiation of cold-water coral growth. (2) Once the cold-water corals established an initial framework, sedimentation becomes an important factor controlling mound growth: the cold-water corals baffle the sediments. (3) Throughout mound growth, the mound may episodically be affected by diagenetic processes responsible for aragonite dissolution and probably carbonate precipitation.

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1. Introduction

The presence of cold-water corals with their associated ecosystems is widespread along the whole European continental margin (Roberts et al., 2006). However, the association of these cold-water corals with the build-up of recent carbonate mounds was until four years ago only well studied in some delineated provinces W of Ireland (Henriet et al., 1998; Kenyon et al., 1998; De Mol et al., 2002; Huvenne et al., 2002). A milestone in the study of the role of cold-water corals in mound build-up was IODP Expedition 307, which drilled in May 2005 “Challenger Mound” in the Belgica Mound Province off western Ireland. The mound body consisted of a 155-m-thick sequence with cold-water coral-bearing sediments of Plio-Pleistocene age (Expedition Scientists, 2005). The success of Expedition 307 paved the way for the further exploration of the diverse world of carbonate mounds.

An exploratory cruise of *R/V Belgica* in 2002 off Larache (Morocco) has led to the discovery of small mounds topping ridges and structural heights, respectively on Pen Duick Escarpment, Renard Ridge, Vernadsky Ridge and Al Idrisi Ridge (Fig. 1). These mounds are

found amidst 9 giant mud volcanoes: the El Arraiche mud volcano field (Van Rensbergen et al., 2005a) (Fig. 1). They occur in a setting where focused fluid seepage is observed (Baraza and Ercilla, 1996; Pinheiro et al., 2003; Somoza et al., 2003; Van Rooij et al., 2005). Because of its unique setting, the carbonate mound site on the Moroccan margin became rapidly involved in a developing stage of focused multidisciplinary research. The high amount of data, acquired recently in these new mound settings on the Moroccan margin, asks for a comprehensive review which will be presented in this paper.

In this paper an overview will be given of the co-occurrence of cold-water corals and carbonate mounds with mud volcanoes (El Arraiche mud volcano field) and active fluid seepage in the Gulf of Cadiz on the Moroccan margin. Attention will be paid to the widespread extinction of healthy cold-water coral frameworks observed nowadays on the Moroccan margin. A three-phase model for carbonate mound development will be proposed. This paper can form the stepping stone for a comparative study between the mounds on the Moroccan margin and global mound occurrences, including the mound provinces in Porcupine Seabight,

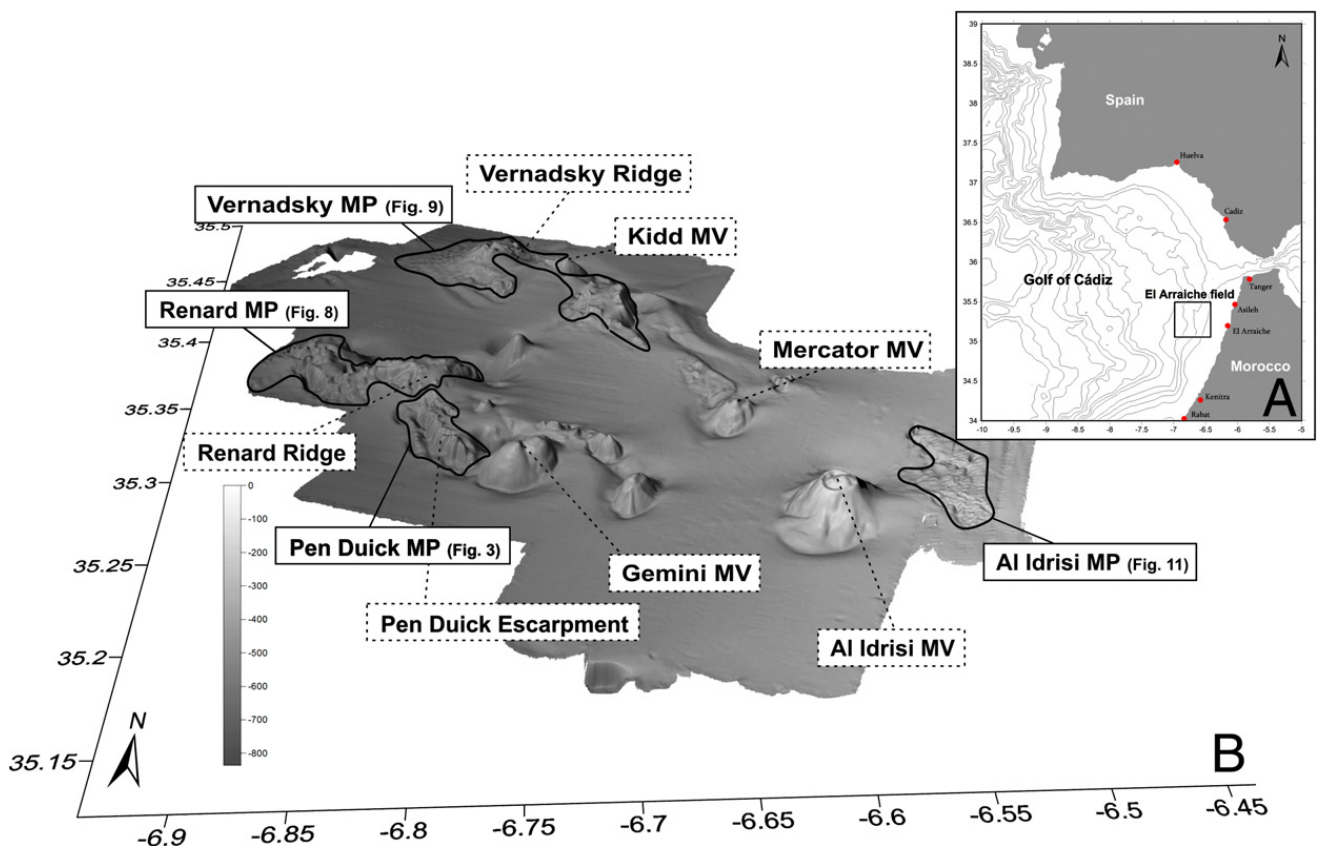


Fig. 1. (A) Location of the study area “El Arraiche mud volcano field” (rectangle) on the Moroccan margin. (B) 3D bathymetric map of the study area. The dashed lines represent the mud volcanoes (MV) and the geomorphological structures. The solid lines indicate the presence of the mound provinces (MP).

off Angola and Congo, Mauritania, Brazil, Florida Strait, Blake Plateau, Orphan Knoll and many more to be unveiled.

2. General setting

2.1. Geological setting

The Gulf of Cadiz is situated west of Gibraltar between 9°W to 6°45'W and 34°N to 37°15'N, enclosed by the Iberian Peninsula and Morocco (Fig. 1A). The geological setting of the Gulf of Cadiz is complex and still under debate (Sartori et al., 1994; Maldonado et al., 1999; Gutscher et al., 2002). The area is characterized by the presence of an accretionary wedge formed by a westward motion of the front of the Gibraltar Arc (the Betic–Rif mountain chain) during the Middle Miocene. Formation of a large olistostrome complex (allochthonous nappes) took place during the Tortonian, as a consequence of increased subsidence (Maldonado et al., 1999). The African–Eurasian convergence since the Cenozoic yields a compressional–transpressional tectonic regime, reactivating many normal faults and causing wide-spread diapirism in the north of the Gulf of Cadiz (Berastegui et al., 1998; Somoza et al., 2003). The main part of the olistostrome unit occupies the central part of the Gulf of Cadiz as a lobe-shaped structure, extending over 300 km into the Atlantic Ocean (Maldonado et al., 1999; Maestro et al., 2003; Somoza et al., 2003; Medialdea et al., 2004).

The study area, El Arraiche mud volcano field, is situated 35 km offshore the north-western Moroccan margin, on top of the accretionary wedge of the Gulf of Cadiz (Van Rensbergen et al., 2005a). The bathymetry is increasing from 200 m to 800 m at the north-western Moroccan continental slope. The study area is characterized by extensional tectonics, in contrast to the main part of the Gulf of Cadiz. This is expressed as large rotated blocks bound by lystric faults that created Plio-Pleistocene depocentres (Flinch, 1993, 1996). In the El Arraiche mud volcano field these rotated blocks are expressed at the seafloor as two subparallel ridges, Vernadsky and Renard Ridges, both with steep fault escarpments, as exemplified by Pen Duick Escarpment (PDE) on Renard Ridge (Fig. 1B). The ridges rise up in water depths of about 700 m and stretch to the shelf edge. Eight mud volcanoes are clustered around these ridges, positioned above large normal faults that bound the rotated blocks and serve as fluid migration pathways fuelling the mud volcanoes (Van Rensbergen et al., 2005a) (Fig. 1B). The source of the overpressured fluids is believed to be located at the base of the accretionary

wedge body since rock clasts in the mud breccia are reported to be of an age up to early Eocene (Ovsyannikov et al., 2003). The onset of mud volcano activity in the El Arraiche mud volcano field is estimated at about 2.4 Ma. Since the Upper Pliocene, episodic expulsion of liquidized sediment created vertical piles of extruded mud up to 500 m thick (Van Rensbergen et al., 2005a).

Geophysical evidence of shallow gas and subsurface fluid flow has been reported in the Gulf of Cadiz (e.g. Baraza and Ercilla, 1996; Pinheiro et al., 2003; Somoza et al., 2003; Depreiter et al., 2005b). Gas hydrates on the Moroccan margin and in the Gulf of Cadiz have only been reported from a small number of deep-water mud volcanoes (Gardner, 2001; Kenyon et al., 2001, 2003; Mazurenko et al., 2003; Pinheiro et al., 2003). Depreiter et al. (2005b) observed anomalous reflections in the Mercator mud volcano and interpreted this as the base of a gas hydrate stability zone. Video imagery visualized the presence of an active ‘brown smoker’ chimney on Mercator mud volcano in a water depth of about 400 m (Depreiter et al., 2005b; Van Rooij et al., 2005).

2.2. Oceanographic setting

The present-day oceanographic circulation in the Gulf of Cadiz is controlled by the exchange of water masses through the strait of Gibraltar and by the interaction of Mediterranean Outflow Water (MOW) with the Atlantic circulation. The highly saline and warm near-bottom MOW flows into the Atlantic Ocean below the less saline, surficial Atlantic Inflow Water (AI) that enters the Mediterranean Sea (Madelain, 1970; Thorpe, 1976; Ochoa and Bray, 1991; Baringer and Price, 1999) (Fig. 2A).

The AI is composed of North Atlantic Superficial Water (NASW) flowing between the surface and a water depth around 100 m and North Atlantic Central Water (NACW) extending between 100 and 700 m (Caralp, 1988) (Fig. 2A). The general surface circulation in the Gulf of Cadiz is anticyclonic with short-term, meteorologically induced variations in the upper layer. It must be considered in relation to the north-eastern Atlantic circulation and could be understood as the last meander of the Azores current. The presence of upwelling regions off the northern margin (Ruiz and Navarro, 2006) (Fig. 2A), can be explained as the direct result of local wind forcing (Garcia-Lafuente et al., 2006).

Below NACW, Mediterranean Water is present. After having passed the Strait of Gibraltar, the MOW undergoes a decrease in temperature, salinity and velocity caused by its rapid mixing with NACW. It then divides into two main cores west of 6°20'W: a Mediterranean

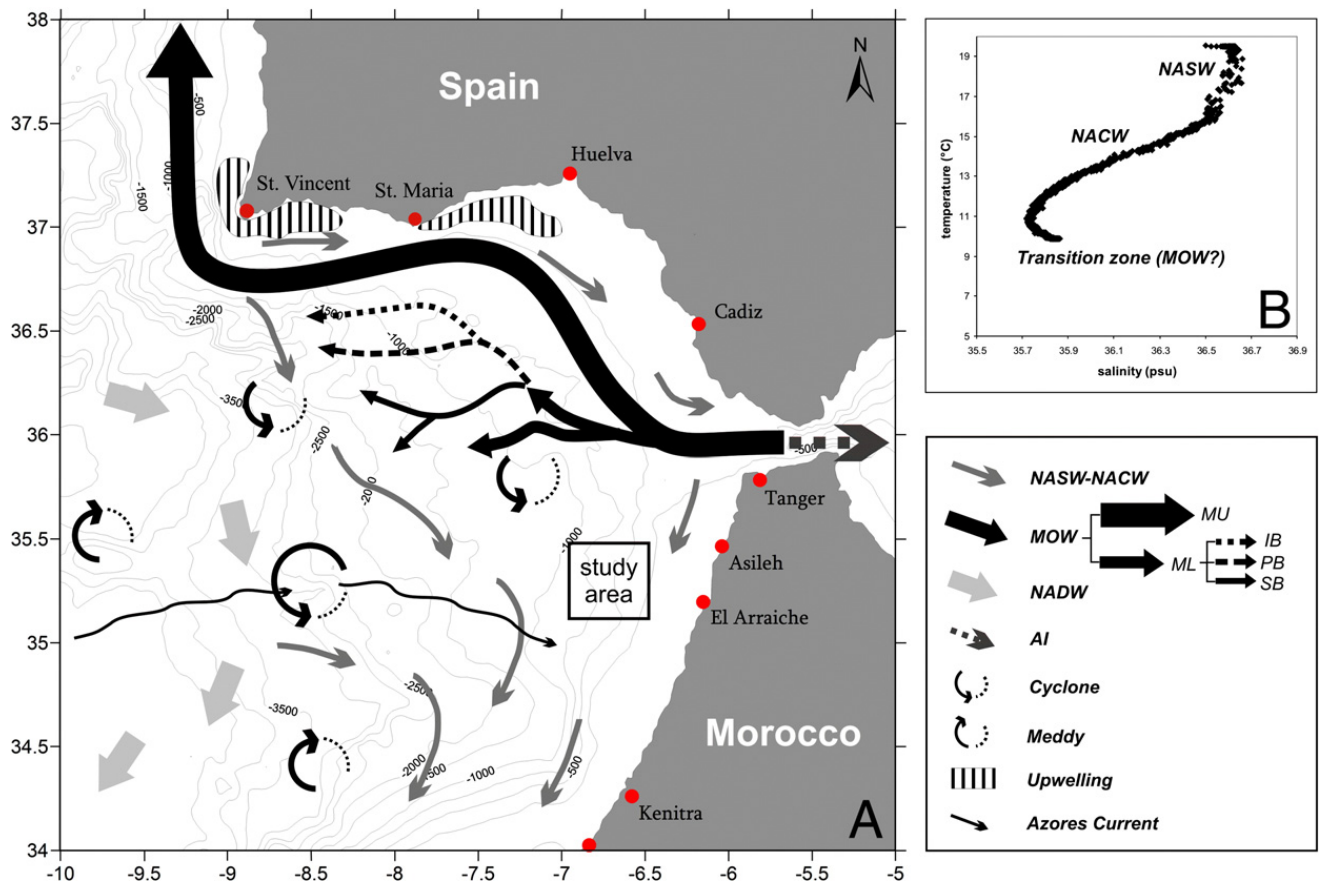


Fig. 2. (A) General circulation pattern in the Gulf of Cadiz (figure modified after Thomson et al., 1999; Schönfeld and Zahn, 2000; Carton et al., 2002; Hernandez-Molina et al., 2003; Vanney and Ménéteau, 2004; Llave et al., 2006; Ruiz and Navarro, 2006) with visualization of North Atlantic Surface Water (NASW), North Atlantic Central Water (NACW), Mediterranean Outflow Water (MOW), North Atlantic Deep Water (NADW), Azores Current, meddies, cyclones and upwelling regions. (B) CTD-profile (temperature versus salinity) characterizing the different water masses in the study area.

Upper Core (MU) and a Mediterranean Lower Core (ML). The upper core is a geostrophically steered current following a northward path along the Spanish and Portuguese continental margin between 400 and 800 m water depth. The lower core is a more ageostrophical current flowing at depths between 800 and 1300 m (Zenk and Armi, 1990; Baringer, 1993; Bower et al., 1997). This lower core is influenced by the morphology of the slope and divided in three minor branches between the Cadiz and the Huelva meridians ($6^{\circ}20' - 7^{\circ}$) (Kenyon and Belderson, 1973; Melieres, 1974; Nelson et al., 1999; Hernandez-Molina et al., 2003): (a) Intermediate Branch (IB), (b) Principal Branch (PB) and a (c) Southern Branch (SB) (Fig. 2A). It has to be mentioned that at Cape St. Vincent the undercurrents veer northwards and become unstable enough to often produce deep anticyclones, called meddies (Bower et al., 1995; Sadoux et al., 2000). Hydrological measurements in 1999 revealed three eddies in the Gulf of Cadiz, displaying substantial interactions: two meddies (meddy Christine, S of Cape St. Vincent and meddy

Isabelle close to the Moroccan margin) and a deep cyclone, which is coupled with meddy Isabelle as a baroclinic dipole (N of meddy Isabelle and SE of meddy Christine) (Carton et al., 2002) (Fig. 2A).

North Atlantic Deep Water (NADW) is present below the MOW at depths > 1500 m (Fig. 2A) (Ambar et al., 2002). It flows from the Greenland–Norwegian Sea region towards the south.

Recent CTD-measurements and current measurements showed that El Arraiche Mud Volcano Field along the Moroccan margin is mainly influenced by NACW (with temperatures between 11 and 16 °C and salinities between 35.6 and 36.5 psu) (Fig. 2B). The typical signature of MOW is not clearly recorded in the study area but the temporarily influence of MOW by meddies cannot be excluded (Fig. 2B). Recent measurements with a BOBO-Lander of the Netherlands Institute of Sea Research (NIOZ), deployed on top of Pen Duick Escarpment, showed the relatively weak effect of internal waves and tidal currents compared to other mound provinces (SE and SW Rockall Trough) (Mienis et al., 2005).

3. Material and methods

The multibeam bathymetry was acquired with a SIMRAD Kongsberg EM1002, installed on board of *R/V Belgica* during the CADIPOR I and II cruises (“Gulf of CADiz — PORcupine Seabight Comparative Study”) in 2002 and 2005, respectively. The data were recorded with a sailing speed of 6 to 7 knots and swath widths ranging from ca. 500 m in deep water to 700 m in shallow water. The beam angles were generally chosen quite narrow (20 to 30°), in order to focus the acoustic energy towards the relatively large depth below the vessel. A spike filter of weak to medium strength was switched on during acquisition. The data were corrected and cleaned with the Kongsberg packages Merlin and Neptune. The footprint at 400 m is 15 × 15 m. In total 725 km² was covered.

High-resolution seismic data were acquired during the CADIPOR I and II campaigns (*R/V Belgica* 2002, 2005) with an 80 electrode 500 J sparker, 35 in³ Soderia GI gun and the Ifremer Deeptow Chirp Sonar System. The seismic profiles were digitally recorded using the Elics Delph system. Data processing (swell-filter, band pass filter, deconvolution and signal amplification) was done using Landmark Promax processing software. Interpretation and mapping was executed in the Kingdom Suite seismic interpretation software package (Seismic Micro-Technology, Inc.).

Sidescan sonar imagery (SSS) was collected with the MAK-1M deep-towed hydro-acoustic complex on board of the *R/V Logachev* during the TTR-12, TTR-14 and TTR-15 cruises in 2002, 2004 and 2005. The MAK-1M deep-towed hydro-acoustic system contains a high-resolution sidescan sonar operating at a frequency of 30 kHz, with a total swath range of 2 km (1 km per side) and a subbottom profiler, operating at a frequency of 5 kHz. The fish was towed at a constant altitude of about 100 m above the seafloor with a speed of 1.5–2 knots. The positioning of the tow-fish was archived by using a short-based underwater navigation system. The data were recorded digitally and stored in SEG-Y format. A time-variant gain control was applied during the acquisition of the data. The processing of the collected data (slant-range-to-ground-range (SLT) correction, geometrical correction and smoothing average filtering) was carried out on board.

Video imagery was collected during the TTR12 cruise with *R/V Logachev* (TVAT33 and TVAT36) and during the CADIPOR II campaign with *R/V Belgica* (c0505-video06) by using a deep-towed frame mounted camera. The imagery was recorded on analog tapes, converted in digital format and imported in a GIS-system (Adélie-GIS 8.3).

6 Hammon grabs (B05-1212, B05-1211, B05-1209, B05-1208, B05-1214 and B05-1215), 2 TV-guided grabs (AT407Gr, AT406Gr) and 1 dredge (AT574D) are used in this study to ground-truth the video material, sidescan sonar imagery and multibeam. The samples were collected respectively during the CADIPOR II cruise (*R/V Belgica* 2005) and the TTR-12 and TTR-15 campaigns (*R/V Logachev* 2002, 2005). One Kasten core (MD04-2804) was collected during the CADICOR cruise in 2004 on board of the *R/V Marion Dufresne* to give insight into the mound structures on PDE. The Kasten core was opened and described in detail. Bulk samples were taken each 20 cm for macrofaunal analysis. Six coral species from the top of the core were sampled for U/Th dating. ²³⁰Th/U datings were measured in the Laboratoire des Sciences du Climat et de l’Environnement (LSCE) in Gif-sur-Yvette with a thermal ionization mass spectrometer (Finnigan MAT262). Five cores (AT564G, AT534G, AT570G, AT571G and AT572G) were acquired during respectively the TTR14 and TTR15 cruises with the gravity corer on board of *R/V Logachev*. The cores were opened and described in detail.

4. Data description and interpretation

4.1. Pen Duick Mound Province

4.1.1. Geomorphology

Extensive multibeam bathymetry and seismics along the top of PDE, a fault-bounded cliff, revealed a series of elongated mounds and mound clusters (Fig. 3). The mounds occur in water depths between 500 and 600 m and can measure up to 60 m in height. They are elongated in E–W direction, with a length of about a half a kilometer. At the base of the cliff smaller mound patches are found, again characterized by an E–W orientation. A NW–SE oriented moat delineates the base of the escarpment. Based on the integration of bathymetry, seismic data and side scan sonar imagery, so far 15 mound structures along the top of the cliff have been identified. The south-west facing part of the cliff has a height of 65 m above the sediments and an average slope gradient varying between 15 and 20°. The eastern edge of the cliff reaches slope gradients up to 25°.

4.1.2. Seismics

A very high-resolution deep-tow chirp seismic profile along the crest of PDE (Fig. 4) shows the mounds as rounded cone shaped features, with a height up to 60 m. No internal structures are observed. On some parts of the profile, mostly between 1500 and 4000 m along the

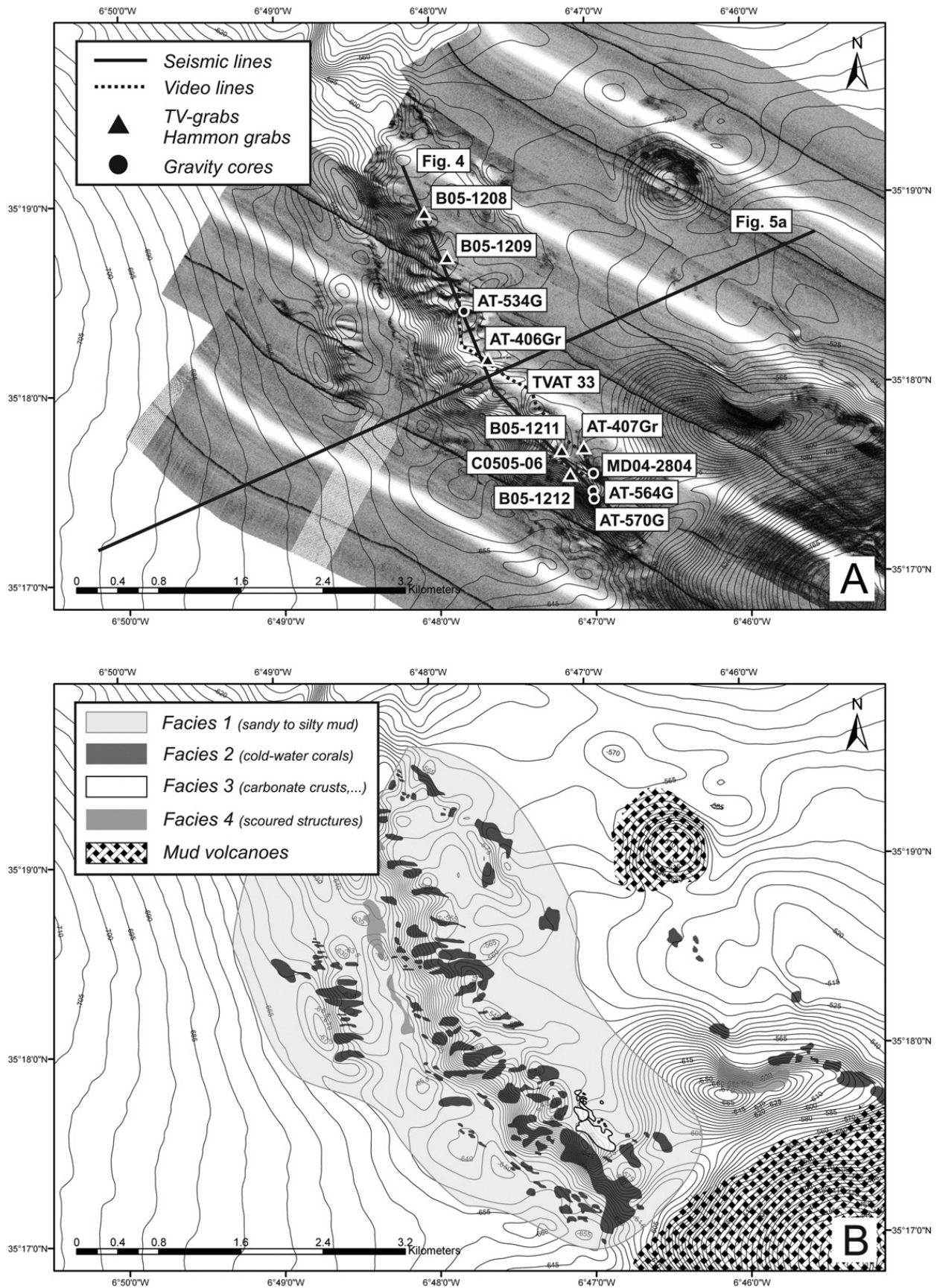


Fig. 3. (A) Bathymetry (contour spacing is 5 m), side scan sonar imagery and location of the seismic profiles, core material and video lines in the Pen Duick Mound Province. (B) Interpretation of sidescan sonar imagery (MAKAT 66-68), representing the four described facies.

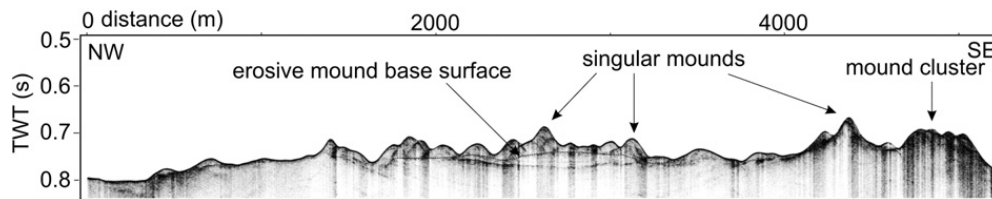


Fig. 4. CHIRP seismic profile (IFREMER) over Pen Duick Escarpment indicating the singular mounds topping the cliff and the erosive mound base surface (location: see Fig. 3A).

distance axis, subsurface reflections are recorded. Generally, the subsurface has a low amplitude. The widely U-shaped geometry of the reflections is caused by directional changes during the acquisition of the data (Fig. 3A). An erosive surface below the mounds can be observed and is interpreted as the mound base.

A profile perpendicular to the PDE shows medium to high amplitude sequences, covering a low-amplitude unit (Fig. 5A). The low-amplitude body has a very steep SW dipping slope beneath the escarpment. Northwards, NE dipping reflections are observed in the low-amplitude unit. The low-amplitude structural acoustic basement, which is part of Renard Ridge, is eroded and crops out at the seafloor. Diffractions at and above the outcropping basement are indicative for the occurrence of elevated mound structures.

A small mound-like low-amplitude body occurs in the high amplitude sequences that cover the basement. Other profiles near the PDE also indicated the presence of small mound-like features in the sedimentary sequences (inset Fig. 5A). Reflections are draping the features, indicating that they are real physical structures. The small mounded features only occur upslope a set of small normal faults associated with gas blanking and bright spots. A direct relation between the two observations is speculative. The features may be interpreted as small buried mounds and could be an indication of the onset of mound growth in the area.

4.1.3. Video imagery and SSS

The integrated analysis of sidescan sonar (MAKAT 66–68), video imagery (TVAT 33 and c0505-video06) and ground truthing by surface coring (AT407Gr, AT406Gr, B05-1212, B05-1211, B05-1209 and B05-1208) revealed four distinctive facies (Fig. 3).

Facies 1 corresponds with sandy to silty clays (Figs. 3 and 6C), characterized by an even surface with some well-delineated patches of cobble to boulder-sized stones. This facies presents the surface sediments in between the different mounds and mound patches. On sidescan sonar imagery it shows low backscatter strength with a very smooth surface. These fine-grained deposits are associated with typical soft-bottom communities (spiral an-

thipatharians, isidiid gorgonians (*Isidella elongata*) and hexactinellid sponges), as well as characterized by a high amount of burrows.

Facies 2 reveals cold-water corals, lying at the surface of the mounds and mound patches along the crest of PDE. Most of the mounds are covered with dead coral fragments and sediment-clogged dead coral rubble, surrounded and overlain by a layer of brownish silty mud (Fig. 6D). The most common observed cold-water coral fragments are classified as *Dendrophyllia* spp. (*D. alternata*, *D. cornucopia* and *D. sp.*), *Lophelia pertusa*, *Madrepora oculata*, *Desmophyllum cristagalli*, and *Caryophyllia calveri*. At the south-eastern edge of PDE the surface units are dominated by *Dendrophyllia* spp. (*D. sp.* and *D. cornucopia*) and some small fragments of *Stenocyathus vermiformis*, as identified in boxcores B05-1212 and B05-1211. Gravity coring (see below) shows that these upper units, built up by mainly *Dendrophyllia* spp., are further down-core replaced by *L. pertusa* and *M. oculata*, associated with *D. cristagalli* and *Caryophyllia* spp. Boxcores B05-1209, B05-1208 and grab AT406Gr learn that more west on Pen Duick Escarpment, the dominating coral species are *L. pertusa*, *M. oculata* and *D. alternata*. A high amount of macrofaunal and microfaunal life is associated with the cold-water coral fragments (crinoids, bryozoans, ophiuroids, gastropods, molluscs, hydroids, serpulids, gorgonians, foraminifers). Mass occurrences of crinoids are observed, using the dead skeletons of cold-water corals as substrate. The cold-water coral patches are characterized by a high backscatter strength and a clear acoustic shadow on sidescan sonar imagery.

Facies 3 consists of carbonate crusts, boulders or hard rock covered by a fine layer of hemipelagic mud (Fig. 6E). Boulder fields, rock outcrops and outcropping carbonate crusts are a common feature in between the mounds. Two distinct patches of carbonate slabs are observed in the eastern part of the TV-line TVAT33, respectively with a length of 11 m and 20 m (Fig. 3B). Solemyid shells, brachiopods (*Megerlia truncata*), dendrophyllid corals, anthipatharians, sponges and calcareous tube worms (Serpulidae) were observed attached on the carbonate crusts (Fig. 6B). It should be noted that the dominating

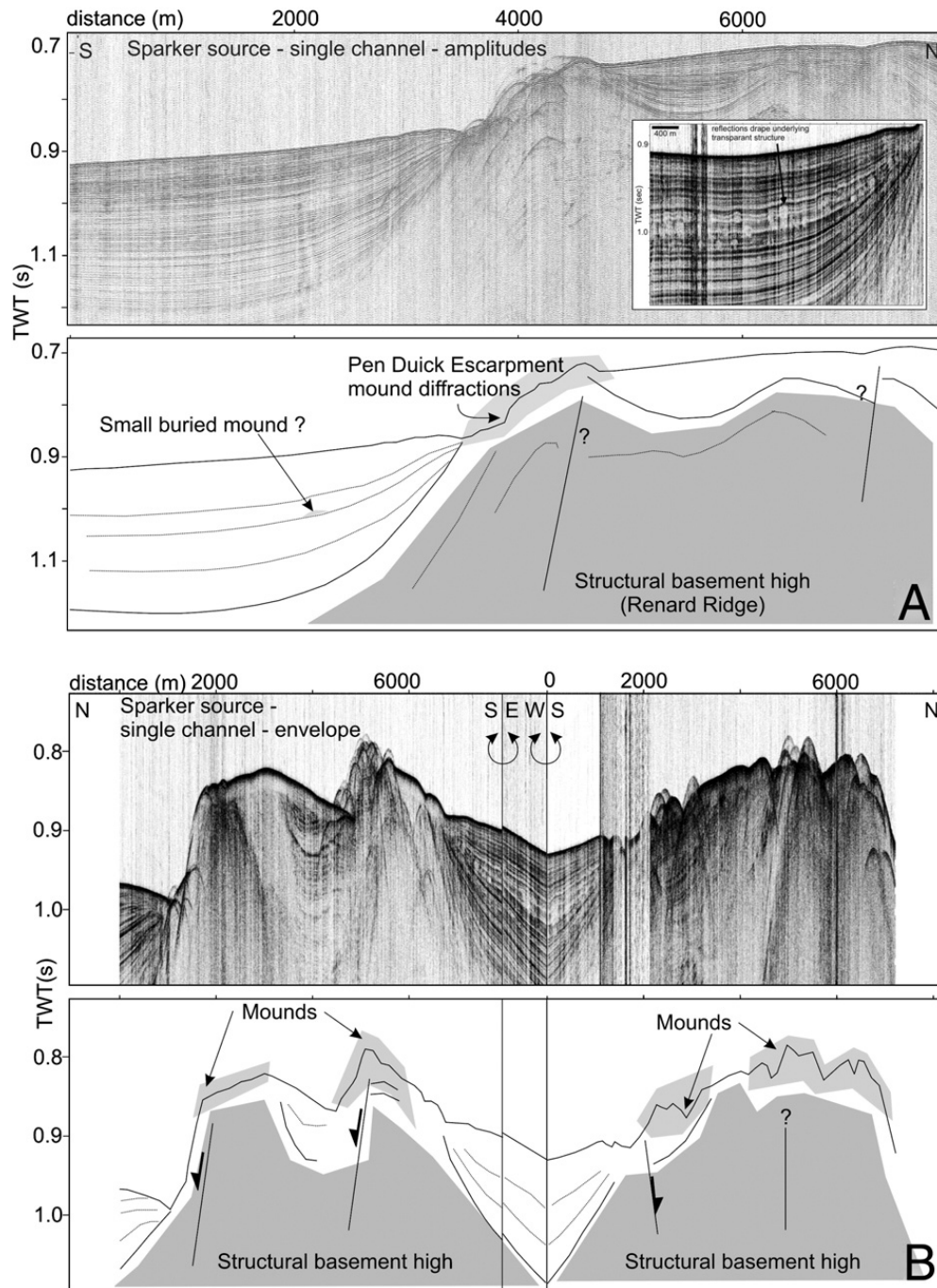


Fig. 5. (A) Sparker seismic profile perpendicular to the PDE, showing the mound diffractions on the escarpment, the structural basement high (location: see Fig. 3). The inset represents some small buried mounds occurring in the sediments at the foot of the escarpment. (B) Set of Sparker seismic profiles over Renard Ridge (location: see Fig. 7). The structural basement, two faults and mound structures can be recognized on the profiles.

cold-water corals associated with these carbonate crusts are mainly *Dendrophyllia* spp. using fossil coral framework and carbonate crusts as substrate. The bivalve *Spondylus gussoni* is often co-occurring with these species on hard substrates.

Facies 4 is recognized on sidescan sonar imagery by its strong backscatter (Fig. 3). It corresponds with the scoured moat at the foot of the escarpment or with a

steep bank or slope, probably created by strong erosive along-slope currents leaving behind a lag deposit of coarser material or dead cold-water coral fragments.

4.1.4. Coring

Four cores, respectively a Kasten core MD04-2804 and three gravity cores AT564G, AT534G and AT570G have been collected on PDE to give insight into the

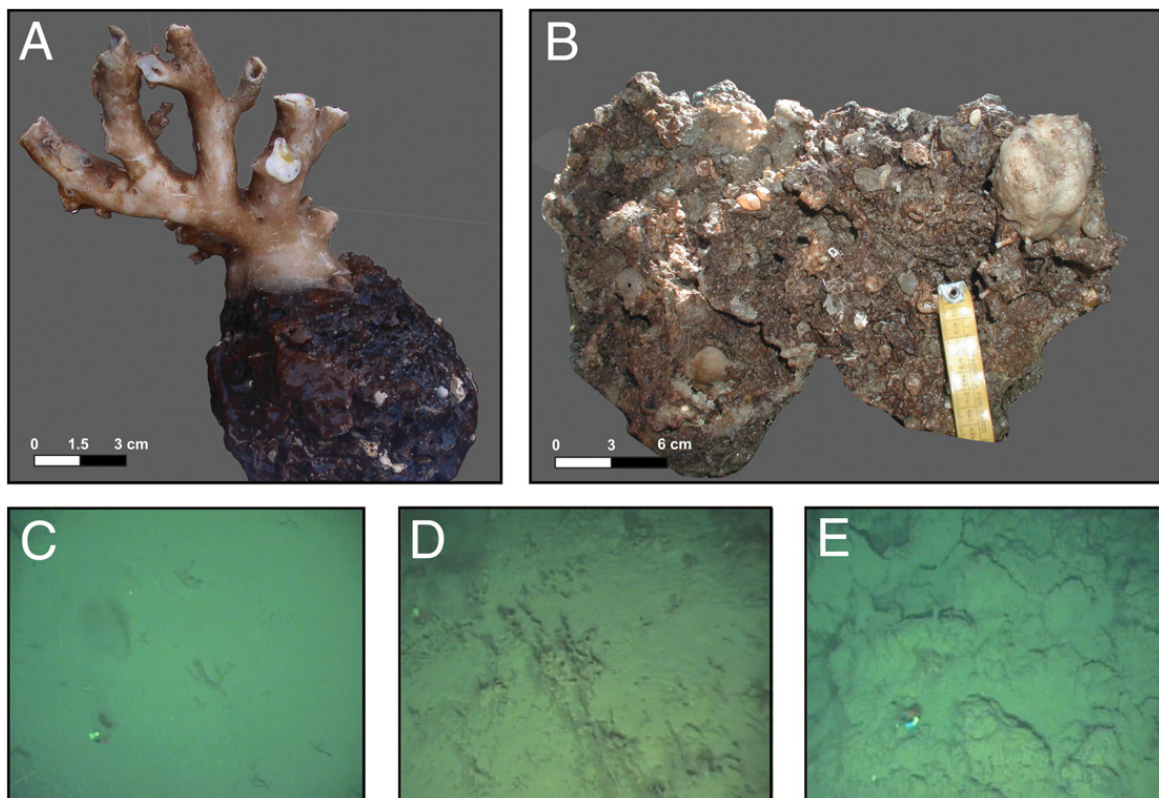


Fig. 6. (A) Cold-water coral *Dendrophyllia alternata* attached on carbonate chimney (station AT574D). (B) Benthic epifauna (bivalves (*Spondylus gussoni*), brachiopods (*Megerlia truncata*), sponges and calcareous tube worms (*Serpulidae*) attached on carbonate crust (station AT407Gr). (C) Video image representing silty mud colonized by spiral anthipatharians and isidiid gorgonians (~ facies 1). (D) Sediment-clogged dead cold-water coral fragments (~ facies 2). (E) Video image showing outcropping carbonate crusts, covered with a thin layer of silty mud (~ facies 3).

mound structures (Fig. 3A). The mound cores display throughout all their penetration depth a high number of reef-forming cold-water scleractinians like *L. pertusa*, *M. oculata*, *D. cristagalli*, *Dendrophyllia* spp. and *Caryophyllia* spp. In association with the cold-water coral fragments numerous shell-bearing invertebrates are determined formerly inhabiting the econiches provided by the coral framework. Based on these observations, every single mound structure on PDE can be interpreted as a cold-water coral mound.

The Kasten core MD04-2804, with a core penetration of 594 cm, is located on the mound cluster at the eastern edge of PDE at a water depth of 505 m (Fig. 3A). The whole core is characterized by cold-water coral fragments embedded in brownish oxidized sandy silt to very fine sand in the top 10 cm grading downwards in silty clays to clayey silts (Fig. 7). The most common colonial cold-water coral species, *L. pertusa*, *M. oculata* and *Dendrophyllia* spp., representing 90% of the total coral content, are alternating in distinctive zones. The upper part, between 0 and 60 cm, is dominated by *Dendrophyllia* spp. (*D. cornucopia* and *D. sp.*) in association with *S. vermiformis* (forming small well-preserved (fossil) specimens up to 2 cm long and 1 to 2 mm wide). Less common in the upper part are *L. pertusa*

and *M. oculata*. *D. cristagalli* occurs as big fragments (up to 5–6 cm) in between the previously described species. Down-core, *L. pertusa* and *M. oculata* are predominating, associated with some specimens of *D. cristagalli* and *Caryophyllia* sp. *Dendrophyllia* spp. is disappearing. As a result of bioerosion and chemical dissolution, the preservation of the coral fragments is rather poor in certain units. In between 215 and 330 cm the cold-water coral fragments are in a very bad stage of preservation mainly due to chemical dissolution (Fig. 7). The density of the coral fragments is changing throughout the core.

Among the cold-water coral fragments, other invertebrate species could be identified. Most of the reported species are known to live in association with cold-water corals. Frequently occurring species were the bivalves *Lima marioni*, *Acesta excavata*, *Asperarca nodulosa*, *Delectopecten vitreus*, *Pseudamussium sulcatum*, *S. gussoni* and *Heteranomia squamula*, the gastropods *Calliostoma* cf. *maurolici*, *Bursa ranelloides*, *Alvania tomentosa*, *Alvania cimicoides* and *Amphissa acute-costata*, the brachiopod species *M. truncata* and *Terebratulina* spp. as well as several echinoderms, e.g. the echinoid *Cidaris cidaris* and mass occurrences of unidentified crinoids. A specific group of bivalves and

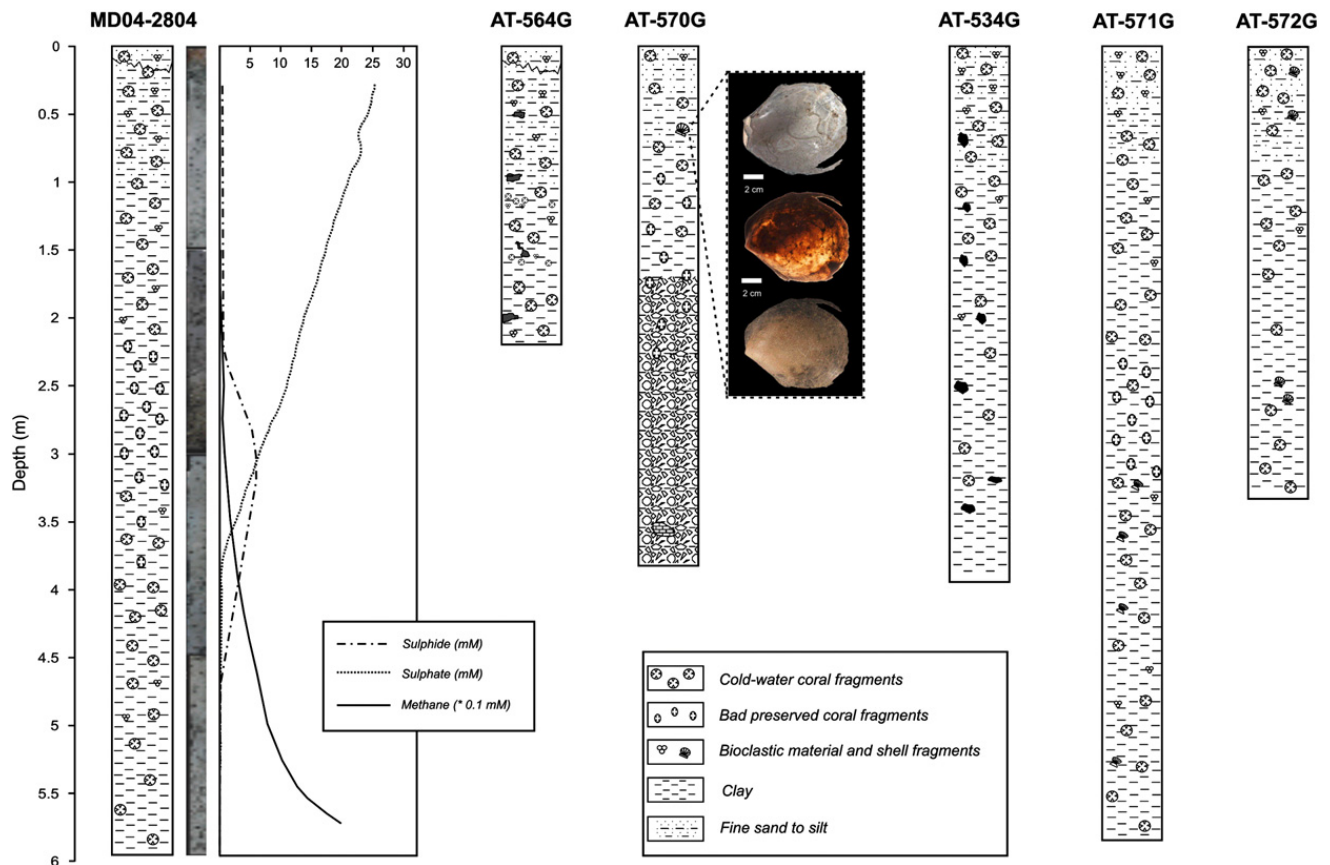


Fig. 7. Description of Kastern core MD04-2804 and gravity cores AT564G, AT570G and AT534G located in the Pen Duick Mound Province and gravity cores AT571G and AT572G, located in the Renard Mound Province. Pore water analysis (sulphate, sulphide and methane) and core images are shown for core MD04-2804. The picture represents an altered bivalve species (*Acesta excavata*), recovered from core AT570G.

gastropods occurring as associates in the cold-water coral environments of the study area are noteworthy as representatives of a local fauna not present in other cold-water coral environments further north. These species are either restricted to the Moroccan margin, at least restricted to the Gulf of Cadiz area (e.g. the gastropod species *A. tomentosa*, *Neptunea contraria*, *Pseudosetia amydraloxy*, *Crisilla amphiglypha* and *Bittium watsoni*) or are part of a fauna not extending further north than the southernmost Bay of Biscay (e.g. *Limopsis angusta*, *B. ranelloides*). These species are of high importance for palaeoenvironmental or oceanographic reconstructions as they are not reported from any other cold-water coral site along the European continental margin. The large bivalve *A. excavata*, on the other hand, implies a clearly boreal influence, nowadays known to be a common and abundant associate to cold-water coral reefs along the Norwegian margin (see López Correa et al., 2005).

Pore water analysis evidences a sharp sulphate-methane transition (SMT) zone at 3.5 m below the mound top, whereas the depth of no sulphate is much deeper in the surrounding sediments (Fig. 7). The horizon characterized by a strong corrosion of the coral

fragments is just lying above and at the front of the recent location of the zone of anaerobic methane oxidation (AOM). Due to the alteration of the cold-water coral fragments, absolute U/Th dating should be questioned (U-series open system behaviour). However, two U/Th datings at 10 and 50 cm core depth yielded confident ages of respectively 290 ± 20 ka and 320 ± 36 ka. Radiocarbon dating on the bivalve *A. excavata*, recovered from the top of the core, yielded ages from more than 50,000 yr BP (Matthias López Correa, pers. com.).

Gravity core AT564G is localized on the same mound cluster as core MD04-2804 at a water depth of 538 m and has a recovery length of 219 cm (Fig. 3). The top of the sediments (0–15 cm) consists of brownish water-saturated very fine sand with coral fragments (Fig. 7), dominated by *Dendrophyllia* spp. in association with *L. pertusa* and *M. oculata*. As in core MD04-2804, also *S. vermiformis*, well-preserved *D. cristagalli* and some *Caryophyllia* spp. fragments are reported in the upper part. The remaining part of the core is represented by a 200-cm-thick horizon of silty clay to clayey silt, with a high amount of *L. pertusa* in alternation with *M. oculata*. *Dendrophyllia* spp. are missing again, while *D. cristagalli*

and *Caryophyllia* spp. are still present in minor quantities. The density of the coral fragments is changing throughout the core. The preservation of the coral fragments is only fair but a well-delineated zone of very badly preserved coral fragments could not be detected. Throughout the succession bioturbations and burrows filled with (soupy) water-saturated clays are observed. Between 116–125 cm and 154–165 cm, an accumulation of smaller coral fragments is noted.

Another core, situated at the south-eastern flank of the same mound cluster as described before and at a water depth of 580 m, is gravity core AT570G. It has a recovery length of 385 cm (Fig. 3). The upper 30 cm are characterized by cold-water coral fragments (dominated by *Dendrophyllia* spp.) embedded in a brownish silty matrix (Fig. 7). Between 0 and 93 cm the brownish silty sediments are grading into grayish silty clays, while the embedded cold-water coral fragments become dominated by the species *L. pertusa* and *M. oculata*. The amount of coral debris is denser at respectively 15–25 cm and 41–80 cm. At 63 cm, a 10 cm large bivalve *A. excavata* was recovered. From 93 cm to 174 cm, cold-water coral fragments embedded in a gray clayey matrix become more and more dissolved (especially between 147 and 174 cm). A remarkable observation is the presence of mud breccia and mud clasts between 174 and 385 cm. From 174 to 231 cm, some coral fragments are still present between the mud breccia and the clay but they disappear completely below this zone.

Gravity core AT534G is retrieved from a mound at the western edge of PDE at a water depth of 550 m (Fig. 3). It has a total length of 395 cm. The presence of large cold-water coral fragments, mainly *L. pertusa* associated with *M. oculata* and big fragments of *D. cristagalli* (up to 3 cm length) in a grayish brown silty matrix are characterizing the uppermost 10 cm of the core (Fig. 7). *Dendrophyllia* spp. (*D. cornucopia* and *D. sp.*) are not present anymore, as observed in AT564G and MD04-2804. Some fragments of *D. alternata* could be identified. Between 10 and 37 cm the silty sediments turn to silty clay. This silty clay is present through the whole core unit until the base, whereas the amount of coral fragments (mainly *L. pertusa*) is decreasing downwards. The bottom part of the core (from 330 cm to bottom) is free of coral fragments. The preservation of the coral fragments throughout the core is rather good.

4.2. Renard Mound Province

4.2.1. Geomorphology

The western edge of Renard Ridge forms a structural high where cold-water corals probably started to build

up mound-like structures (Fig. 8). The western part of the ridge has a height of 100 m above the seafloor. The top of the ridge is covered with mound clusters and single mounds occurring in water depths between 550 and 700 m. Single mounds are reaching a height up to 30 m. The mounds are smaller than the mounds reported along the PDE. Cold-water coral patches are present on the sediments flanking the western and south-western sides of the ridge. The total amount of mounds and cold-water coral patches can be estimated at 65. As observed on PDE, the mounds and patches are elongated. A clear E–W oriented moat is present at the north-eastern part of the ridge which shows a slope inclination of 23°.

4.2.2. Seismics

A set of seismic profiles, jointly shown in Fig. 5B, shows the occurrence of many mounded features at the culminations of the low-amplitude acoustic (and structural) basement. The two sides of the profile are mirrored sections of the ridge — the ends of the profile are located north, the central part of the profile south (Fig. 8). The presence of at least two large normal faults can be inferred from the data. A first fault occurs at the northern side of the ridge and dips towards the north. At the surface, the basement crops out. Along the ridge, elevated features are indicating the presence of mound structures. Further southwards, a second normal fault with a large offset again disrupts the seafloor. A large set of diffractions is again interpreted as the presence of mounds on top of the outcropping basement. The height of the mounds reaches several tens of meters.

4.2.3. Video imagery and SSS

The combination of sidescan sonar imagery (MAKAT 75) and ROV video imagery (TVAT 36) made it possible to delineate the different patches and mounds covered with mainly dead cold-water coral fragments, identified as *L. pertusa*, *M. oculata* and some *D. alternata*. It corresponds with facies 3 as described on PDE (Figs. 6 and 8). It should be noted that the corals are more densely branched and form higher frameworks in comparison to PDE, where most of the corals are present at the seafloor as smaller fragments and branches. Anthipatharians, large reddish alcyonaceans, sponges and many crinoids use the dead cold-water coral fragments as substrate. Facies 1, consisting of sandy to silty mud, is draped over whole the ridge and forms the main facies between the mounds and cold-water coral patches (Figs. 6 and 8). As on PDE, this mud layer is colonized by typical soft-bottom communities (spiral anthipatharians, isidiid gorgonians and hexactinellid sponges). Bioturbation and burrows are common.

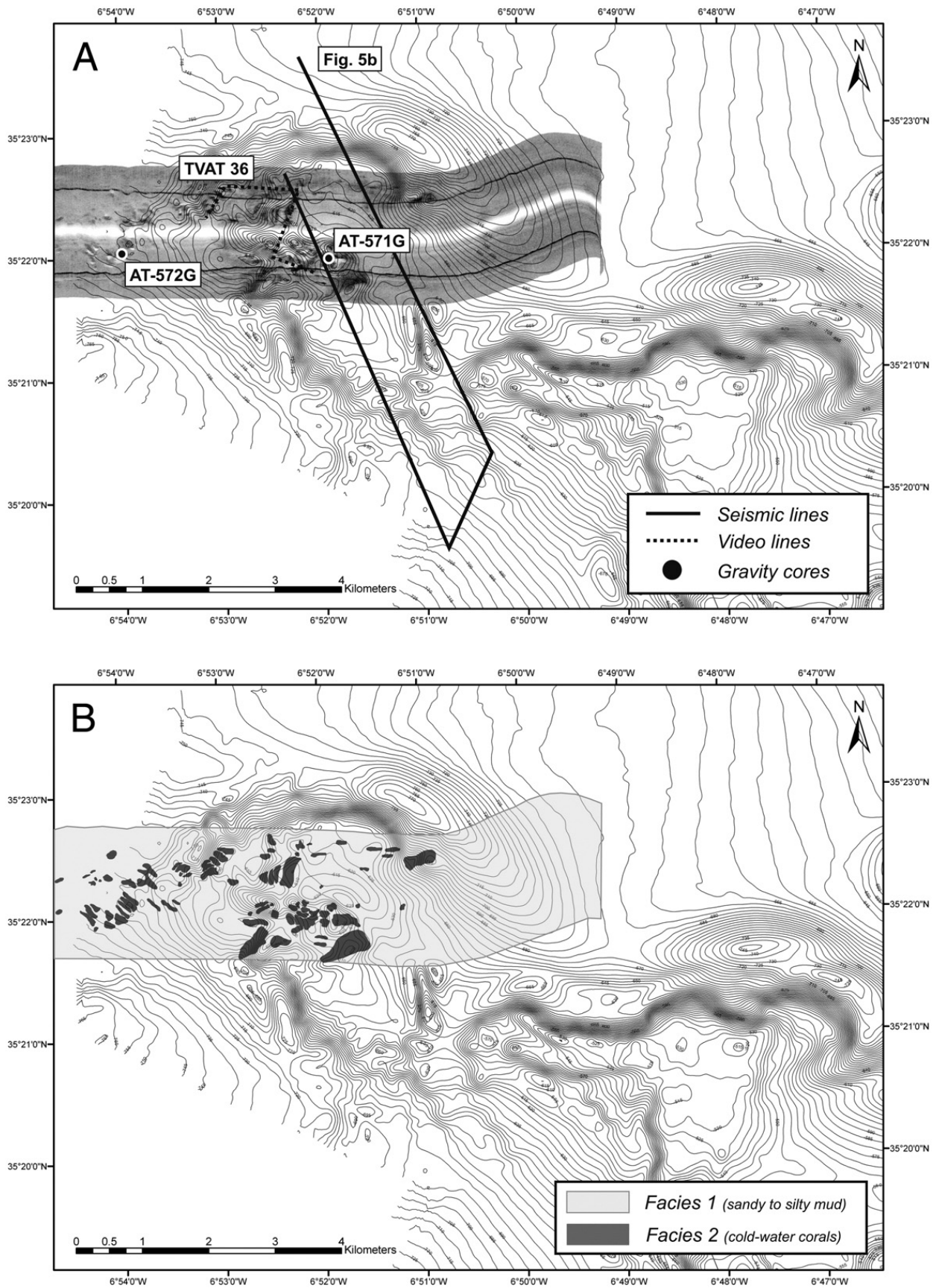


Fig. 8. (A) Bathymetry (contour spacing is 5 m), side scan sonar imagery and location of the seismic profiles, core material and video line in the Renard Mound Province. (B) Interpretation of sidescan sonar imagery (MAKAT 75), representing two distinctive facies.

Some boulders, colonized by benthic epifauna, are present between the mounds.

4.2.4. Coring

Two gravity cores have been collected at the western edge of Renard Ridge, respectively AT571G on top of a small mound on Renard Ridge and AT572G on top of a cold-water coral patch in the sediments flanking Renard Ridge (Fig. 8).

Gravity core AT571G has a recovery length of 581 cm and is localized on top of a small mound at a water depth of 580 m. Coral fragments are present throughout whole the core length but the density of coral fragments changes (Fig. 7). The main coral fragments are identified as *L. pertusa* and *M. oculata*. Less abundant are the species *D. cristagalli*, *D. alternata* and *Caryophyllia* spp. The determined species of the coral fragments are alternating in different zones, whereby in certain units *L. pertusa* seems to dominate, while in other zones *M. oculata* takes the overhand. The matrix in the upper 37 cm consists of brownish sandy silt going over in silty clay becoming more compact towards the bottom. Bioclastic fragments from bivalves, gastropods (including pteropods), echinoids, crinoids, bryozoans, crustaceans and serpulids are present between the coral fragments. Planktonic and benthic foraminifera are common. Badly preserved and heavily dissolved coral fragments are frequently observed between 250 and 300 cm. The colour of the sediments in which the corals are embedded becomes lighter in and especially below this unit.

Core AT572G, with a recovery length of 333 cm, is acquired on top of a cold-water coral patch on the flank of Renard Ridge at a water depth of 712 m. Coral fragments are present in the upper 70 cm but their amount is decreasing by going downwards (Fig. 7). The upper brownish sandy silt (0–70 cm) grades into grayish silty clay to dark clay at the bottom. The most abundant coral species are identified as *M. oculata* and *L. pertusa*. The coral fragments in the upper zone are rather well-preserved.

4.3. Vernadsky Mound Province

4.3.1. Geomorphology

The northern edge of Vernadsky Ridge is densely covered by small mound-like structures while mound-like patches are found on the sediments flanking the ridge (Fig. 9). The mounds on top of the ridge reach heights up to 50 m and widths up to 250 m. The mounds and mound patches are elongated and seem to be lined up, following the structural height. They occur in water depths between 700 and 500 m. The south-western flank

of the Vernadsky Ridge has a gentler slope than the north-eastern flank, reaching maximum slope values of about 23°. A small NW–SE directed moat is present at the south-western flank, while deeper scoured moat structures are observed at the other side of the ridge. The total amount of mounds and cold-water coral patches on this northern edge of the Vernadsky Ridge can be estimated at 130.

The central part of the Vernadsky Ridge consists also of a topographic height, providing substrate for the settlement of benthic organisms. At the edges, mound-like structures are recognized, which can be interpreted as small NW–SE orientated mound patches. They have a similar acoustic signature on seismics and sidescan sonar imagery as the mound-like structures at the northern edge of Vernadsky Ridge (Fig. 9).

4.3.2. Seismics

Seismic profiles over the central part of the Vernadsky Ridge give insight into its structure. Fig. 10A shows the outcropping and eroded low-amplitude acoustic basement being covered by younger sequences. Correlation of the seismic data around the ridge culmination indicated that a large normal fault had been active during the past. This has created an offset of about 400 m at the ridge crest. Northwards of the large normal fault, smaller faults are found, which could either be antithetics from the main fault, or a consequence of sediment removal in the subsurface due to mud volcano activity.

In the vicinity of this structurally active place, acoustic diffractions are observed (Fig. 10B). Some diffractions clearly stand out above the seafloor and thus can be interpreted as mound structures. The seismic data retrieved at the northern part of the Vernadsky Ridge are densely populated by acoustic diffractions (Fig. 10C). Structural basement highs are separating small intraridge basins. These are likely to be fault-controlled. Nearly the whole seafloor reflection is obscured by diffractions. The diffraction height runs up to 50 m and their width up to 200 m. These diffractions are again interpreted as mound diffractions, indicating that nearly the whole seabed is covered with mound build-ups and mound patches.

4.3.3. SSS

Sidescan sonar imagery (MAKAT 107–108) revealed similar acoustic signatures as observed on Renard Ridge and PDE (Fig. 9). The mound structures and mound patches are characterized by a high backscatter strength and a clear acoustic shadow, and can be interpreted as cold-water coral carbonate mounds and/or cold-water coral patches (cf. facies 2 on PDE and Renard Ridge). In between the mound patches, a smooth

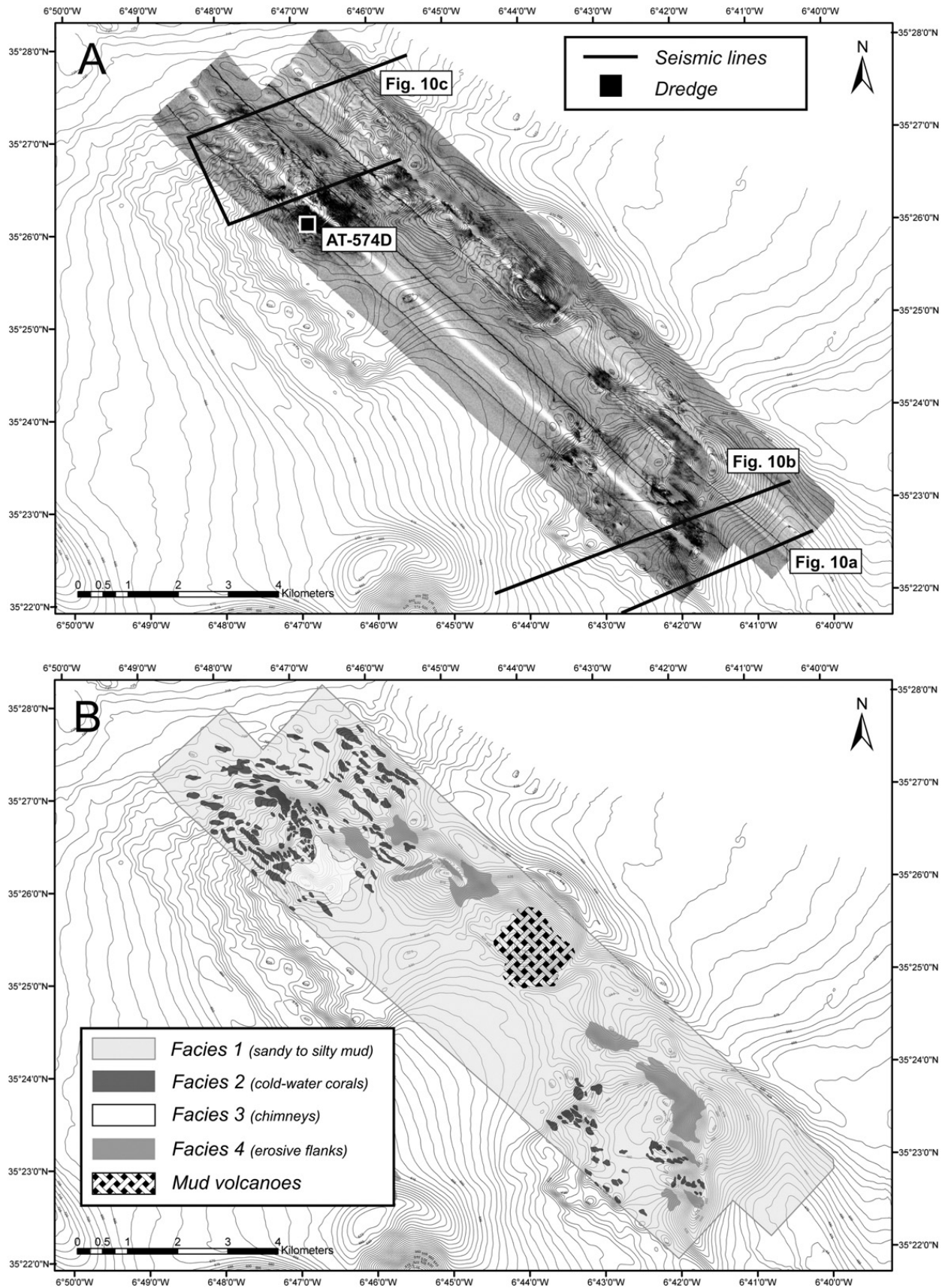


Fig. 9. (A) Bathymetry (contour spacing is 5 m), side scan sonar imagery and location of the seismic profiles and core material in the Vernadsky Mound Province. (B) Interpretation of sidescan sonar imagery (MAKAT 107-108), representing four distinctive facies.

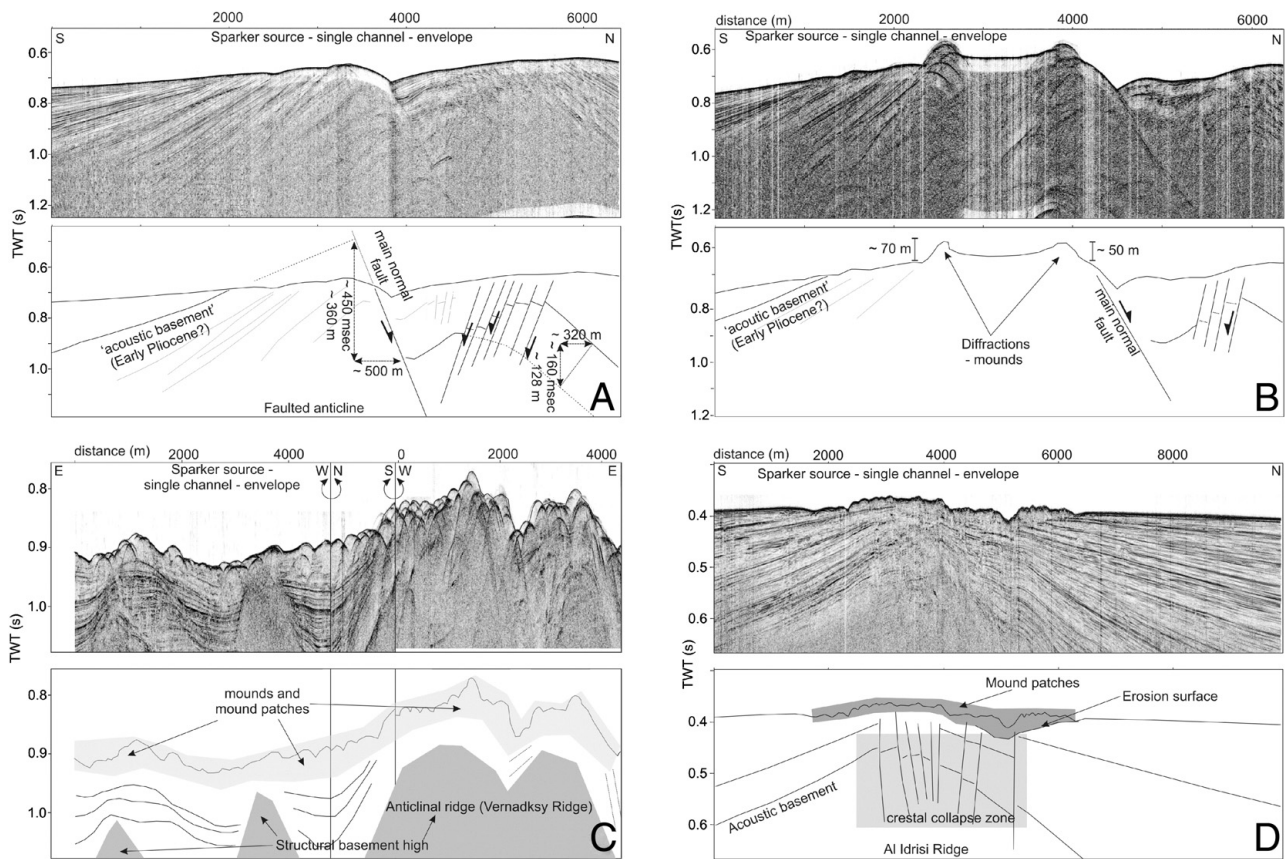


Fig. 10. (A) Sparker seismic profile over the central part of Vernadsky Ridge (location: see Fig. 9), showing the outcropping acoustic basement as well as a normal fault and a set of smaller faults giving insight into the structure of the ridge. (B) Sparker seismic profile over the central part of Vernadsky Ridge (location: see Fig. 9), representing a set of diffractions on top of the basement, which can be interpreted as mound structures. (C) Set of seismic profiles over the northern part of Vernadsky Ridge (location: see Fig. 9), showing the dense population of different mounds and mound patches and the structural basement highs separated by small intraridge basins. (D) Sparker seismic profile in Al Idrisi Mound Province (location: see Fig. 11), representing the Al Idrisi Ridge and a set of small mound-like features on the sediments burying the ridge.

surface with low backscatter intensity is observed, corresponding with sandy to silty clays (facies 1). Kidd mud volcano can be clearly delineated (Fig. 9). Another area with high backscatter intensity is located on top of Vernadsky Ridge. Ground truthing using a dredge (station AT574D), revealed that this area with high backscatter corresponds with the presence of carbonate crusts and chimneys. Serpulids, bivalves (*S. gussoni*), bryozoans, dendrophyllid corals, etc. use the chimneys and crusts as substrate to settle on (e.g. Fig. 6B: *D. alternata* attached on chimney). Also the steep north-eastern flanks with their associated NW–SE orientated scoured moats, are characterized by higher backscatter strengths.

4.4. Al Idrisi Mound Province

4.4.1. Geomorphology and SSS

East of mud volcano Al Idrisi, mound patches on a much smaller scale are observed (Fig. 11). They appear on multibeam bathymetry and sidescan sonar imagery as small E–W aligned mound-like features, not higher than 10 m and in rather shallow water depths (350 to 200 m).

Ground truthing by Hammon grabs (B05-1214 and B05-1215) revealed that the structures are covered with cold-water coral fragments, dominated nearly exclusively by *L. pertusa* and *M. oculata*, embedded in brownish oxidized silty clays, which grade into grayish and stiff silty clays.

4.4.2. Seismics

Below the Al Idrisi mud volcano, an anticline is buried below the sedimentary sequences. The crest of the low-amplitude basement, culminating at less than 100 m below the seafloor, is highly fractured and has collapsed in response to sediment withdrawal by mud volcano activity. Several bright spots indicate the presence of gas in the sediments at shallow positions. Mound-like features with a low-amplitude and chaotic internal facies are topping the anticline culmination area at the seafloor. Below the chaotic facies, an erosive surface is present (Fig. 10D). The chaotic mounded features can be interpreted as small coral patches, what is confirmed by sampling. The erosive surface is interpreted as the base of the mounds.

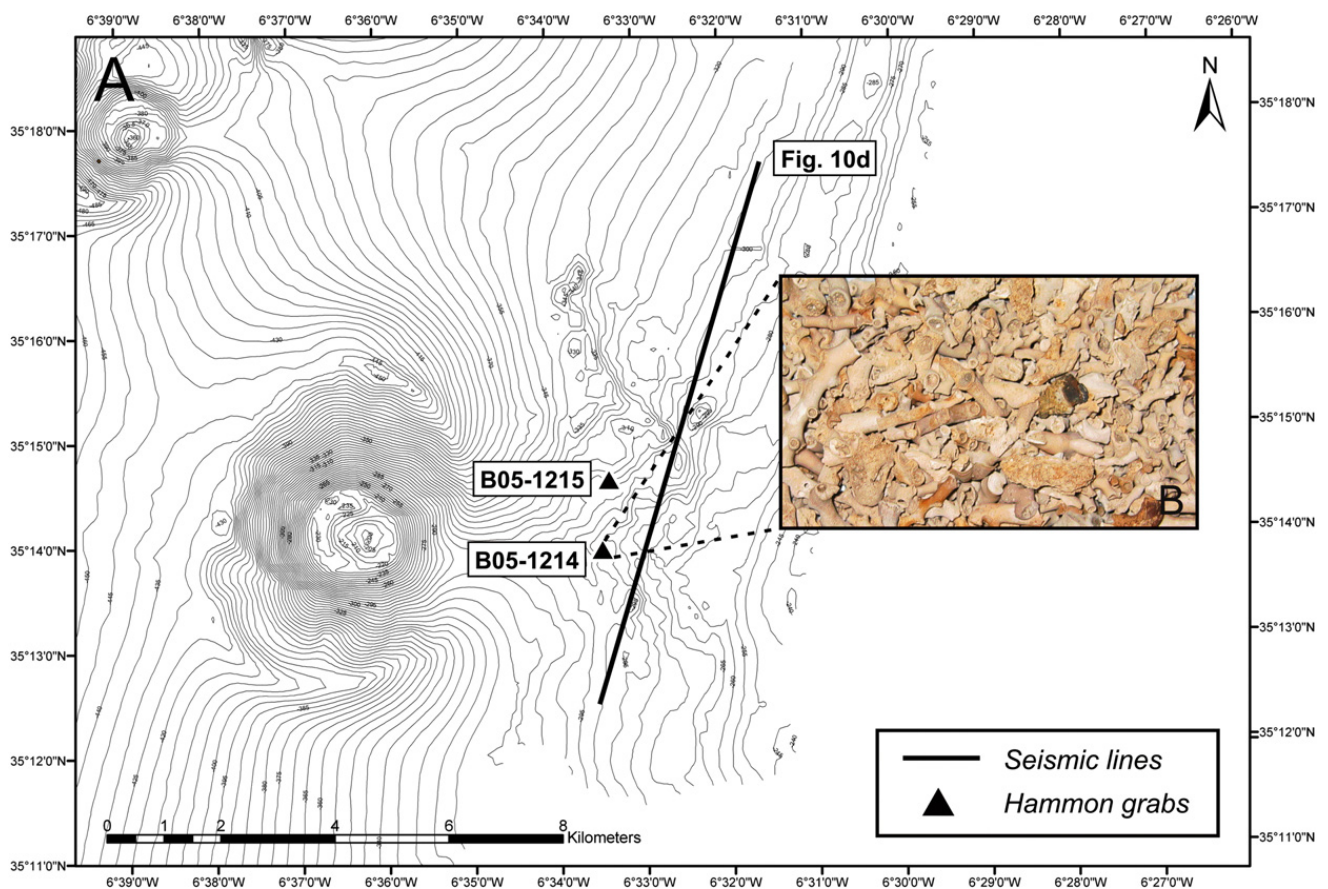


Fig. 11. Bathymetry (contour spacing is 5 m) and location of seismic profile and core material in the Al Idrisi Mound Province. Inset presents the dead cold-water coral fragments (mainly *Lophelia pertusa* and *Madrepora oculata*), recovered from the surface.

5. Discussion

5.1. Initiation of cold-water coral growth

As shown before seismic data reveal a close association between the anticlinal ridges and mound structures. In El Arraiche mud volcano province, cold-water coral mounds show to be closely related to the Renard, Vernadsky and Al Idrisi Ridges. While Renard and Vernadsky Ridges show nowadays outcropping basement, Al Idrisi Ridge is entirely buried, with indications of gas occurrence in the sediments above the ridge. Several explanations for this co-occurrence between mounds and ridges seem to be possible.

The erosive basement surface could have created a prime hard substrate for coral larvae to settle on. The more, by forming seafloor elevations these basement ridges can create enhanced currents and thus a higher food particle flux which forms the base for a highly active planktonic food chain, which is often regarded as an important factor in the process of cold-water coral growth: “the highest on the elevation, the more food” (Mortensen, 2000; Freiwald, 2002; De Mol et al., 2002). Moreover, the effect of tidal waves, as reported on PDE by Mienis et al. (2005), may have enhanced seabed food supply at an initial stage. The external input of nutrients driving cold-water coral growth is not the only factor controlling mound build-up. Sediment input is another important factor for mound growth, whereby cold-water coral colonies on elevated structures are baffling transported sediments to build up mounds (Foubert et al., 2005a; Huvenne et al., 2005; Wheeler et al., 2005a).

As Al Idrisi Ridge does not show a clear topographic elevation that would have favoured cold-water coral growth as explained in scenario 1, the main reason for initial cold-water coral growth might have been the presence of a suitable settling ground. Because Al Idrisi Ridge is clearly buried, with the cold-water coral build-ups not related to the basement, hardgrounds may have been an initial substrate. Hardgrounds could have been created by gas or fluid seepage cementing partly the seafloor.

5.2. Extinction of cold-water corals

Another phenomenon is the wide-spread extinction of cold-water corals on the Moroccan margin, Gulf of Cadiz. So far, no extensive live frame-work building corals could be observed. In contrast, healthy living coral colonies are observed on the Norwegian margins up to the north (e.g. Freiwald et al., 1997, 2002; Hovland and Mortensen, 1999; Fosså et al., 2005), in Rockall Trough

and on Rockall Bank (e.g. Akhmetzhanov et al., 2003; Kenyon et al., 2003; van Weering et al., 2003), on Porcupine Bank (e.g. Wheeler et al., 2005b), in Porcupine Seabight (e.g. Foubert et al., 2005a; Huvenne et al., 2005; Wheeler et al., 2005a), and south of the Galicia Bank (Duineveld et al., 2004). The cold-water corals and their associated ecosystems in the Mediterranean Sea are already in a stage of retirement since the onset of the Holocene (Taviani et al., 2005). The coral fragments appearing at the surface in the southern part of the Gulf of Cadiz are rather old, reaching ages older than 300 ka (~ MIS 9) at the south-eastern edge of Pen Duick Escarpment.

However, the presence of clear mound structures built up by cold-water corals evidences that in the recent geological past, environmental and oceanographic conditions were suitable for prolific cold-water coral growth. Before the onset of the recent interglacial conditions, the Gulf of Cadiz was much more influenced by a North Atlantic regime (Vanney, 2002), resulting in a descent of the polar front (until Portugal), decrease in temperatures, lowering of the general sea level (100–120 m), influence of icebergs and their associated ice rafted debris from the north (even up to south of the Gulf of Cadiz) (Heinrich events, Lebreiro et al., 1996). Llave et al. (2006) and Voelker et al. (2006) suggested that the lower Mediterranean branch with a significantly higher salinity and density (Schönfeld, 1997; Zahn et al., 1997; Cacho et al., 2000), enhanced during climatic coolings (glacials/stadials). This lower branch of intensive and deeper MOW (Thomson et al., 1999; Schönfeld and Zahn, 2000; Rogerson, 2002) results in a stronger interaction with the seafloor and higher current velocities (Llave et al., 2006). The enhancement of the lower core of MOW (mainly the Principal and Southern Branches) during previous glacial conditions can have enhanced the formation of meddies (carriers of cells of MOW with their full biological content), which have probably strongly influenced the Moroccan Margin. Several molluscan and foraminiferal species co-occurring with the cold-water corals, as observed in the Kasten core MD04-2804 and the surface boxcores, belong to a Mediterranean fauna, indicating an important influence of MOW in the past. The bivalve species *L. marioni* and *S. gussoni* are preferably occurring in areas with a clear influence of MOW. Molluscan species such as the bivalves *Microgloma tumidula* and *Yoldiella wareni* or the gastropod species *Drilliola emendata* and *Alvania electa* are mainly occurring in areas under the influence of MOW. Moreover, the study of an off-mound core (Vanneste, 2005) between Renard Ridge and Vernadsky Ridge, showed the presence of coarser and more reworked material during colder

periods, indicating higher currents which can be linked with the input of more vigorous meddies and the interaction of these meddies with NACW. These meddies and the interaction of these meddies with NACW, are responsible for a fresh supply and a higher flux of nutrients, which is positive for prolific cold-water coral growth (Freiwald et al., 2002).

Nowadays, all the cold-water coral fragments and mounds are draped by a fine layer of silty mud. The off-mound core between Renard Ridge and Vernadsky Ridge is characterized by finer sediments since the onset of the Holocene and a rather high sedimentation rate (18.5 cm/ka) could be calculated for this period (Foubert et al., 2005b). The deposition of finer sediments since the onset of the Holocene evidences that currents are nowadays probably weaker than during glacial times. It can be postulated that a major change in oceanographic conditions since the onset of the Holocene, together with a decrease in the food particle flux and higher sedimentation rates, are responsible for the death of most of the cold-water coral colonies. Moreover, large-scale changes in oceanography may have an effect on small-scaled tidal current systems, which might explain the relatively weak tidal currents nowadays reported by Mienis et al. (2005) in the southern Gulf of Cadiz along the Moroccan margin.

It is worth to mention that the environmental and oceanographic situation described for colder periods on the Moroccan margin, can be nowadays observed in well-delineated areas of Porcupine Seabight, where cold-water corals are still alive (De Mol et al., 2002; Foubert et al., 2005a; Huvenne et al., 2005; Wheeler et al., 2005a). Current regimes in Porcupine Seabight and along the Moroccan margin seem to be opposite to each other during glacial and interglacial periods (at least for the most recent ones).

5.3. Cold-water coral dissolution and carbonate precipitation

The growth of cold-water corals and the origin of carbonate mounds was a heavily debated subject during the last decade. Different theories were invoked concerning cold-water coral growth and the development of carbonate (mud) mounds built up by cold-water corals. Cold-water coral reefs on the Norwegian margins and carbonate mounds in Porcupine Seabight were supposed to be related with light hydrocarbon seepage (Hovland, 1990; Hovland et al., 1998; Henriot et al., 1998, 2002). Hovland and Mortensen (1999) suggested a new hydraulic theory relying on the assumption that there is a stable local input of nutrients through the seabed at or

near the location where the reefs are found. Recent research learns that an external flux of nutrients (with optima at boundaries between different water masses) and an active planktonic food chain, based on a higher primary productivity in surface waters and subsequent food transport to the sea floor is the main factor controlling cold-water coral growth (Duineveld et al., 2004; Roberts et al., 2006) and so mound build-up.

In the Gulf of Cadiz, on the Moroccan margin, mounds built up by cold-water corals occur in an area characterized by the presence of gas seepage and subsurface fluid flow. However it should be noted that no direct relationship could be found between cold-water coral growth and fluid or gas seepage. On the other hand, a positive relationship between focused fluid flow and carbonate mound distribution on the south-eastern edge of PDE is observed. This is evidenced by a rather high sulphate gradient, with a methane oxidation front at 3 m below the surface measured on core MD04-2804 (Fig. 7). Three main reasons can be invoked to explain a higher internal methane flux towards the mounds at the south-eastern edge of the ridge. First of all, a mounded feature on a scarp or a hill on the seabed subjected to rather strong peak currents will develop zones of high pressure at the lows of the slopes and low pressure areas at or near the summit (Depreiter et al., 2005a). This pressure effect would create a fluid migration from deeper layers to the top of the structure. This effect will be enhanced at the edges of a ridge, where higher pressure gradients are created. So, in this view, the pumping of fluids in carbonate mound systems is driven by external currents. Another reason is the association of the mounds with the ridges, and thus with the faults co-occurring with the ridges. Indeed, as observed on the seismics, the ridges are partly fault-controlled. The faults can be preferable pathways for fluids, canalizing the fluids towards the mounds on top of the ridges. A third reason can be the influence by the recent eruptive activity of the neighbouring Gemini West mud volcano, focusing the extrusion of fluids towards the mud volcano crater. Van Rensbergen et al. (2005b) has shown that Gemini West mud volcano is one of the most active mud volcanoes in the region, as it lacks a hemipelagic sediment drape of fine mud (as observed over most of the mud volcanoes, mounds, carbonate slabs and covering the seafloor in between the mounds) and it features a shallow sulphate reduction zone (as observed in the Kasten core MD04-2804). The presence of mud breccia and mud clasts in gravity core AT570G (at the south-eastern flank of a mound at the south-eastern edge of PDE), confirms the influence of the recent activity of mud volcanoes on this south-

eastern edge. The mud breccia and clasts recovered in this core are similar to the mud breccia and clasts recovered from cores on the neighbouring mud volcanoes (Van Rensbergen et al., 2005b).

The cold-water coral fragments embedded in the sediments, as observed in well-delineated parts of the studied cores, are heavily dissolved. This phenomenon is clearly observed in core MD04-2804, whereby the cold-water coral fragments are in a rather bad stage of preservation due to dissolution just above and at the front of the recent zone of anaerobic oxidation of methane. This can be explained by a pure diagenetic process (resulting from the fluxes in pore water transport). Oxidation of organic matter alters the pH and the alkalinity of interstitial water and thus the diagenesis of carbonate minerals (Tribble, 1993). In general, model results indicate that mineral saturation states decrease during oxic respiration (from release of carbonic acid) and increase during sulphate reduction (from increase in alkalinity) (Jørgensen, 1983; Reeburg, 1983). The C:N ratio of the organic matter and the degree to which sulphide precipitates as a mineral phase also affect the saturation state with respect to carbonate minerals. Tribble (1993) suggested that the aragonite saturation state initially drops but becomes oversaturated during extensive sulphate reduction. A pattern of initial aragonite dissolution followed by carbonate precipitation as a function of the extent of sulphate reduction can occur within reefs in a manner similar to that described for sediments (Tribble, 1993). Throughout this process the interstitial waters keep close to equilibrium compositions with aragonite. This buffers the pH of the waters. Because interstitial water in the reef has a short residence time, the observed equilibration suggests rapid kinetics. A similar process is noted in the mounds in Porcupine Seabight SW of Ireland, where no obvious recent methane fluxes or seepage is noted (Foubert et al., 2007). However, when a flux of methane reaches the aerobic zone, aerobic methane oxidation takes the overhand and drops the pH drastically, stimulating a net dissolution of aragonite. During coupled anaerobic methane oxidation and sulphate reduction, HCO_3^- and HS^- are released, increasing the pH and so stimulating a system that becomes oversaturated in respect to aragonite, resulting in carbonate precipitation. Precipitation of sulphides as FeS strongly affects the aragonite saturation state. So, focused and alternating fluxes of methane in time can stimulate dissolution of cold-water corals in the aerobic zone and precipitation of carbonate in the anaerobic zone. However, no distinctive zones of explicit carbonate precipitation are noted in the studied cores, while extensive horizons of coral dissolution are clearly present. More focused geochemical

research on the carbonate-rich fractions and the pore fluids have to be carried out in order to understand the processes behind carbonate dissolution and precipitation and the possible effect of alternating fluxes of methane in time. Despite the fact that the exact mechanisms are not yet completely understood, it can be assumed that mounds, built up by the interaction between sediment dynamics and coral framework, can be affected by the dynamics of internally controlled pore water fluxes.

While cold-water coral growth has obviously nothing to do with seepage, the mounds they create by the interaction between sediment dynamics and coral framework can be affected by internally controlled fluid fluxes.

5.4. A “three-phase” model for the development of carbonate mounds

By combining the observations, a three-phase mound development model can be proposed for the mounds on the Moroccan margin:

- (1) In a first stage the cold-water corals start to colonize a suitable substrate under specific environmental and oceanographic conditions, positive for cold-water coral growth. The most important factor is the presence of a planktonic food chain, based on a high primary production and an enhanced food particle flux towards the seafloor. Elevated positions (e.g. Renard and Vernadsky Ridges, Pen Duick Escarpment), creating enhanced currents and so a higher nutrient flux, are preferable. Tidal currents may have at this stage an additional positive effect on the availability of planktonic food particles for cold-water corals.
- (2) During a second phase, the interaction between sediments, currents and cold-water corals plays an important role. As described in Porcupine Seabight, sedimentation and hydrodynamics regulated by oceanographic and climatic changes are crucial in mound development (De Mol et al., 2005; Dorschel et al., 2005; Foubert et al., 2005a; Frank et al., 2005; Huvenne et al., 2005; Rüggeberg et al., 2005; Wheeler et al., 2005a). The initial cold-water coral frameworks start to baffle sediments under certain current regimes, a crucial phase to build up mounds. In this phase, coral colony development and sediment baffling proceed in harmony. When sedimentation prevails, cold-water corals can be buried. On the contrary, when no sediments are available the polyps can be kept sediment-free and cold-water corals can build healthy reef frameworks (cold-water coral reefs) up to several meters high, as

observed on the Norwegian margins (Freiwald et al., 2002).

- (3) In a last phase, when the cold-water corals are embedded in a sediment-rich matrix and when an initial mound structure is already built, fluid seepage and fluxes in pore water transport affects the built structures by diagenetic processes, resulting in for example cold-water coral dissolution (as observed on the mounds on Pen Duick Escarpment and Renard Ridge). It should be mentioned that the last phase can be concurrent with phase 2. A continuous interaction between the different phases is responsible for the final character of the mound structures.

6. Conclusion

The mound and mound patches in El Arraiche mud volcano field can be divided in four well-delineated provinces: Pen Duick Escarpment (Pen Duick Mound Province), western edge of Renard Ridge (Renard Mound Province), Vernadsky Ridge (Vernadsky Mound Province) and Al Idrisi Ridge (Al Idrisi Mound Province). The mounds are highest and most developed on PDE, while the Al Idrisi patches are just characterized by small elevated structures (up to 3 m). The Renard Ridge mounds and Vernadsky Ridge mounds have many similarities, whereby most of the mounds are observed on top of the ridges and fading out mound patches are colonizing the sediments burying the flanks of the ridges. The seismic data confirmed a close association between the anticlinal ridges at or below the seafloor, and the mound structures built up by cold-water corals on the seafloor.

The gravity cores, boxcores and video imagery display a high number of reef-forming cold-water scleractinians like *L. pertusa*, *M. oculata*, *Dendrophyllia* spp., *D. cristagalli* and *Caryophyllia* spp. with numerous faunal associations formerly inhabiting the econiches provided by the coral framework. Temporal and spatial variations are observed in the dominance of the different cold-water coral species. Under present interglacial environmental and oceanographic conditions, no healthy live coral reefs could be observed. However, environmental and oceanographic conditions during colder periods (glacials/stadial) where probably more favourable for cold-water coral growth. Meddies, anticyclonic cells of MOW, and the interaction of these meddies with NACW, could have played hereby a major role.

Fluid seepage can affect the built mound structures by diagenetic processes, resulting in cold-water coral dissolution. However, no obvious relation between cold-water coral growth and seepage is observed.

A three-phase model for the mound development on the Moroccan margin can be proposed. During a first phase the cold-water corals start to colonize suitable substrates under specific environmental and oceanographic conditions positive for cold-water coral growth. In a second stage, the cold-water coral frameworks start to baffle sediments regulated by environmental changes and build up cold-water coral mounds. During the last phase, fluid seepage affects the initial structures by diagenetic processes. The continuous interaction between the last two phases, which may be concurrent, is responsible for the final character of the mounds.

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