VARIABILITY IN PLEISTOCENE TO RECENT SEDIMENTATION FROM THE CARBONATE MOUND PROVINCES IN THE PORCUPINE SEABIGHT, NORTHEASTERN ATLANTIC: IMPLICATIONS FOR CARBONATE MOUND GROWTH AND DEVELOPMENT.

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ABSTRACT

The Porcupine Seabight (PSB) on the Irish continental margin contains three distinct carbonate mound provinces with many of the individual mounds being colonised by the cold-water azooxanthellate corals *Lophelia pertusa* and *Madrepora oculata.* The oceanographic regime in the PSB is one of the main controls on the location and development of these mounds. For these sea floor structures bottom currents play an important role and nowadays in the PSB the Mediterranean Outflow Water (MOW) appears to be crucial for the living cold-water coral ecosystems on these carbonate mounds.

The variability in present day bottom current speeds on Propeller Mound were studied from modern sedimentation. The dominant current direction in the Porcupine Seabight is from south to north, although at Propeller Mound the currents are deflected in a southwesterly direction. Grain size and compositional analyses of box core surfaces taken from the seafloor adjacent to and from Propeller Mound in the Hovland Mound Province show that the intensity of these currents varies locally. Highest current speeds occur to the west of the mound and on the mound surface, winnowing away finer sediment fractions (clay-fine silt) and leaving coarse sortable silt and sand lag deposits. Coarse grains are absent from the seafloor to the east of the mound. Local forcing of bottom currents is likely due to the elevated topography of the mound and tidal currents in the area. Sediments from Propeller Mound contain elevated calcium carbonate contents (50%) compared to background sediments (39%) what is proportional to the volume of coarse bioclastic material present.

The hydrodynamic variability recorded in Pleistocene drift sediments was studied in a more southerly mound province. Analysis of core MD-01-2450 from the Belgica Mound Province documents drift sedimentation in an off-mound location reaching far beyond 200 kyr B.P. An hiatus representing >160 kyr is present, separating an upper silty drift body containing abundant coarse ice rafted debris (IRD) from a finer grained glacial unit below. This hiatus is represented as a coarse sandy unit interpreted as a debris flow or slump. The sedimentary record indicates that glacial periods in the PSB were periods of reduced bottom water circulation, with variability in the size range of IRD delivered to the seafloor.

Changes in the geological and biological record in Propeller Mound are related to changes in hydrodynamics associated with glacial and interglacial cycles. Down-core variability in grain-size and bioclastic composition through Propeller Mound suggests that current speeds have not been stable in the on-mound environment through time. Sediments aged between 0.27 and 1.5 Ma (Marine Isotope Stages 9 to 50) show that the sediment composition on the mound has changed considerably and repetitively through time. Four sedimentary facies have been identified in the mound and are related to current intensities and glacial – interglacial cycles. Fine grained mudstones and wackestones are deposited during glacial periods and coarse coral grainstones and packstones are the result of concentrating bioclastic remains through winnowing during interstadials. These units are formed by relatively high current speeds and often represent hiatuses. An indication of a fluctuating current regime is correlative with the faunal assemblage recorded in the sediment, with corals dominating interstadial/interglacial units and suspended sediment tolerant bryozoans occurring in the finer grained sections of the core. The different facies units are stacked and repeated; indicating that Propeller Mound has been able to continuously re-establish itself as an active mound community, despite the influence of a fluctuating current regime during the last 1.5 Ma. Calculated sediment accumulation rates of 1.12 cm/ky for the cored section and 7 cm/ky for the un-penetrated mound section have implications for previously proposed mound growth models. The values indicate that a very rapid 'booster stage' must be recorded in the unpenetrated depths of the mound, and that Propeller Mound has entered the 'coral bank' or 'burial' stage with a shift to lower sediment accumulation rates. It is likely that the dominant sediment type preserved in the unpenetrated section is likely to be a wackestone, with fewer hiatuses and occurrences of grain- and packstones than in the cored interval.

ZUSAMMENFASSUNG

Am Irischen Kontinentalhang in der Porcupine Seabight (PSB), befinden sich drei Karbonathügelgebiete, in denen viele der einzelne Hügel durch die Kaltwasserkorallen *Lophelia pertusa* und *Madrepora oculata* kolonisiert sind. Das ozeanographische System der PSB ist eine der Haupeinflussfaktoren bezüglich der Position und der Entwicklung dieser Karbonathügel. Für diese Strukturen sind die Bodenströmungen von großer Bedeutung und heutzutage spielt in der PSB vor allem das Mittelmeerausstromwasser (MOW) eine wichtige Rolle für die dort lebenden Kaltwasserkorallenökosysteme auf den Karbonathügeln.

Korngrößenanalysen und Untersuchungen der Kernoberflächen von Kastengreifern vom Propeller Mound in der Hovland Mound Province und vom umgebenden Meeresboden, zeigen das die Intensitäten dieser Bodenwasserströmungen lokal unterschiedlich sind. Die höchsten Strömungsgeschwindigkeiten befinden sich westlich und auf der Oberseite des Karbonathügels und erodieren feinere Sedimente (Ton bis feine Siltfraktion), lassen aber die gröbere sortierte Silt- und Sandfraktion liegen. Östlich des Hügels gibt es keine Ablagerungen von groben Sedimenten. Lokale Anstiege der Bodenwasserströmungen lassen sich auf die erhöhte Topographie am Karbonathügel und auf Gezeitenströmungen zurückführen. Sedimente vom Propeller Mound besitzen im Vergleich zu anderen Sedimenten, durch den höheren Anteil von groben bioklastischen Materials, einen höheren Gehalt an Kalziumkarbonat (~50% im Gegensatz zu 39% in den umgebenden Sedimenten).

Veränderungen in der Hydrodynamik, wie sie in Driftsedimenten aufgezeichnet werden, wurden in einer weiter südlich gelegenen Karbonathügelprovinz untersucht. Sedimentologische Analysen des „off-mound“ Kerns MD-01-2450 aus der Belgica Mound Province, dokumentieren die Ablagerung von Driftsedimenten weit über die letzten 200.000 Jahre hinaus. Ein Hiatus in der stratigraphischen Abfolge repräsentiert >160.000 Jahre und trennt zwei unterschiedliche Sedimentschichten: Eine obere Schicht aus siltigen Driftsedimenten mit einem hohen IRD Gehalt, und eine unterlagernde feinkörnige glaziale Schicht. Der Hiatus wird repräsentiert durch eine grobkörnige sandige Schicht, welche als Turbidit oder Hangrutschung interpretiert

wird. Die sedimentäre Abfolge zeigt, dass in der Porcupine Seabight während glazialer Abschnitte niedrige Bodenwasserströmungen vorherrschten.

Schwankungen in der Korngröße und der bioklastischen Zusammensetzung innerhalb des untersuchten Kerns vom Propeller Mound führen zu der Annahme, dass die Bodenwasserströmungsgeschwindigkeiten im Laufe der Zeit variierten. Die Sedimentabfolge zwischen 0.27 und 1.5 Ma (marine Isotope Phasen 9 bis 50) zeigt, dass sich die Zusammensetzung der Sedimente wiederholt im Laufe der Zeit geändert hat. Vier sedimentäre Fazies, die auf Bodenwasserströmungen und glaziale-interglaziale Abschnitte zurückzuführen sind, konnten am Propeller Mound identifiziert werden. Feinkörnige ‚Mudstones' und Wackestones' haben sich während glazialer Zeiten abgelagert, die grobkörnigen mit Korallen angereicherten, Grainstones' und ‚Packstones' stammen aus interstadialen Zeiten. Diese Einheiten wurden durch hohe Bodenwasserströmungsgeschwindigkeiten und geringe Sedimentationsraten geformt und repräsentieren häufig Hiatusse. Ein Hinweis auf die schwankenden Strömungsgeschwindigkeiten lässt sich in den biologischen Ablagerungen im Sediment nachweisen. Kaltwasserkorallen dominieren die zwischeneiszeitlichen/interglazialen Sedimentschichten, während Bryozoen in den feineren Schichten des Kerns vorkommen. Die Abfolge dieser vier Faziestypen in den Kernen vom Propeller Mound wiederholt sich mehrmals. Daraus lässt sich schließen, dass sich der Propeller Mound trotz der Einflüsse der schwankenden Bodenwasserströmungen, im Laufe der letzten 1.5 Ma immer wieder aktiv und kontinuierlich aufgebaut hat. Kalkulierte Sedimentationsraten von 1.12cm/kyr für den Kern des beprobten Abschnitts des Propeller Mounds und 7cm/kyr für den unbeprobten Teil, unterstützen ältere Karbonathügelwachstumsmodelle. Die Werte zeigen zum Einen, dass eine sehr schnelle „Booster-Stage" in einer noch nicht beprobten Tiefe des Hügels vorhanden sein muss und zum Anderen, dass der Propeller Mound mit dem Übergang zu langsameren Sedimentationsraten die „Coral-Bank"- oder „Burial"-Stadien erreicht hat. Es ist anzunehmen, dass das dominierende Sediment in den noch unbeprobten Schichten des Propeller Mounds ein „Wackestone" ist. Im Gegensatz zu den beprobten Schichten ist außerdem mit weniger „Grainstone" oder „Packstone" Ablagerungen und einem geringeren Hiatusvorkommen zu rechnen.

CONTENTS

CHAPTER 1: Introduction

The carbonate mound provinces of the European North East Atlantic Margin have been intensely studied in the past decade (e.g. De Mol et al., 2002; De Stigter et al., 2001; Masson et al., 2003; Wilson and Herbon, 1998). Geological interest expanded in the early nineties when scientists postulated relationships between carbonate mounds (and their related cold-water coral ecosystems) and oceanographic conditions (Freiwald, 2002; Mortensen et al., 2001) or hydrocarbon seeps on the seafloor (Hovland et al., 1994). Since then, the corals and the structures they build have been the subject of several international European research projects. Scientists from various European institutions have attempted to contribute to the understanding of the onset of the growth of these structures, their stabilisation, and what role oceanography, bacteria, corals, hydrocarbons and argillaceous sediments may play in their development. These cold-water carbonate reef environments have been discovered from North West Africa to the Barents Sea, and their importance has been heightened by the recognition of their high biodiversity and relationship to North Atlantic fisheries.

The carbonate mounds addressed in this study occur in the Porcupine Seabight (PSB) off the coast of south western Ireland where they are found in three mound provinces: the Belgica, Hovland and Magellan Mound Provinces. These provinces have been delineated on the basis of different mound morphologies, and are thought to share a common initiation period during the Early Pliocene (De Mol, 2002). The dominant mound building organisms in the PSB today are the cold-water azooxanthellate corals *Lophelia pertusa* and *Madrepora oculata* (Freiwald, 2002; Huvenne et al., 2002a).

Several different models for carbonate mound growth and development in the PSB have been postulated (Henriet et al., 1998; 2002; De Mol, 2002; Rüggeberg et al., in press: Dorschel et al., 2005). These have been based on seismic and side scan sonar studies and analyses of short (< 6m) core from the mound surfaces. All studies have shown that hydrodynamics are a controlling factor for mound development, and evidence of bottom current activity in the mound provinces today is interpreted from scoured moats, drop-stone pavements, outcropping hardgrounds, drift sediment bodies and dunes and ripples on the seafloor (Hovland et al., 1994; Wheeler et al., 1998a; Henriet et al., 1998; 2002; De Mol et al., 2002; Rüggeberg et al., submitted, Rüggeberg et al., 2005; Van Rooij et al., 2003; Huvenne et al., 2002a; 2003; Huvenne, 2003; Dorschel et al., 2005; Foubert et al., 2005).

The sediments used in this study have been sourced from Propeller Mound, (the largest carbonate mound in the Hovland Mound Province) and from the seafloor adjacent to Challenger Mound (in the Belgica Mound Province).

AIMS

The aims of this thesis are:

1) To investigate the hydrodynamic variability recorded in Pleistocene drift sediments from the Belgica Mound Province (Chapter 3).
2) To determine the variability in bottom current speed over Propeller Mound from modern drift sediments (Chapter 4).
3) To relate changes in the geological and biological record from Propeller Mound to hydrodynamic changes in the PSB driven by glacial-interglacial cycles, as well as presenting new age data for Propeller Mound with consequences for the application for previously proposed mound growth strategies (Chapter 5).

REGIONAL SETTING

The Porcupine Seabight: Physiography

The PSB is a NE-SW oriented amphitheatre shaped embayment on the Irish Atlantic shelf 150 km long, 65 km across in the north and widening to 100 km in the south (Figure 1.1). Water depths gradually increase from 300 m in the north to more than 2000 m in the south where the basin opens out onto the Porcupine Abyssal Plain. The

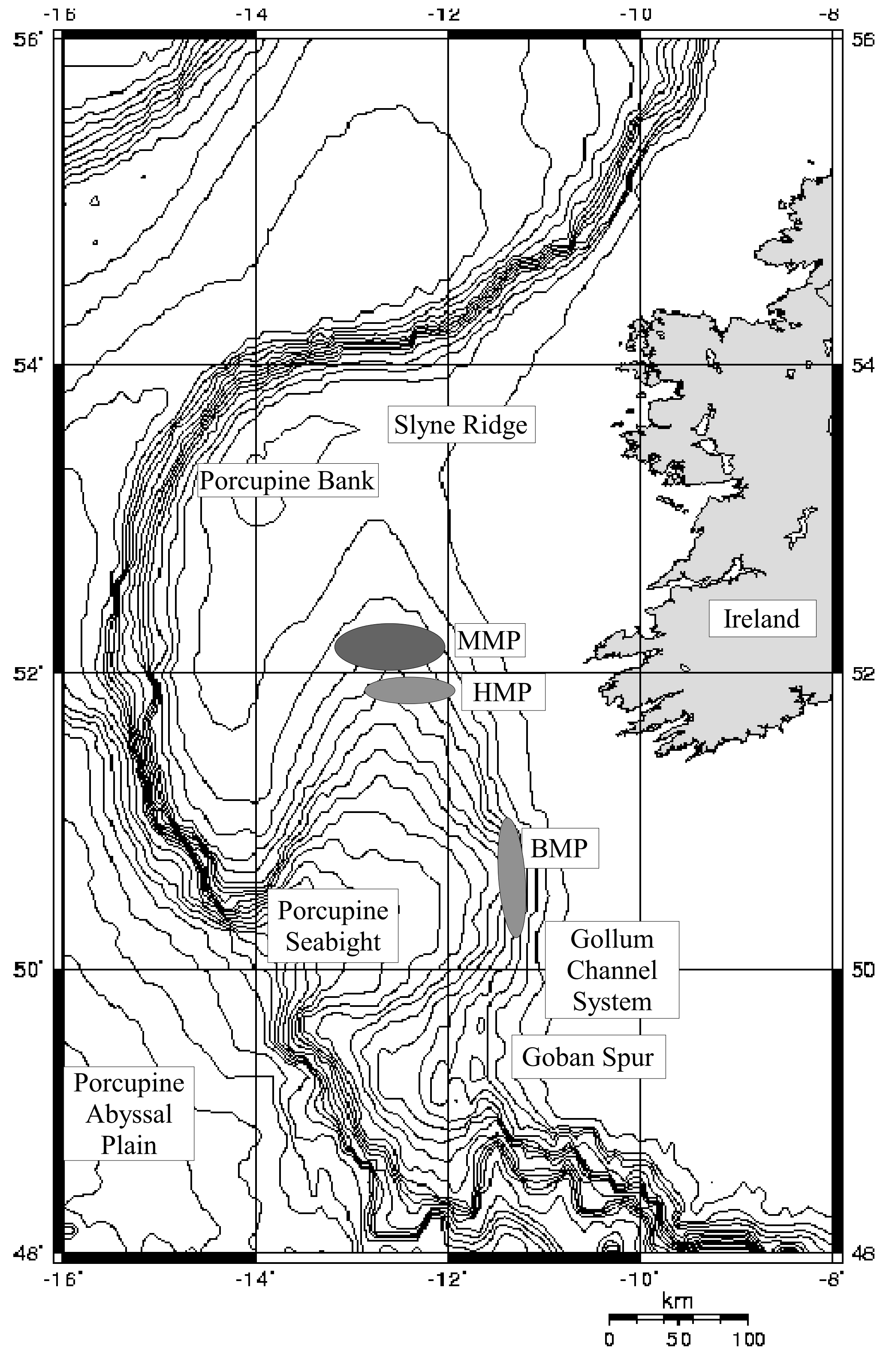

Figure 1.1: Location of the Porcupine Seabight on the North Atlantic margin, southwest of Ireland. Also shown are the location of the three carbonate mound provinces, Belgica Mound Province (BMP), Hovland Mound Province (HMP) and Magellan Mound Province (MMP).

average slope of the basin is approximately 0.5˚, although steeper inclinations of 2-3˚ occur along its western and eastern flanks.

The PSB is bounded to the north by the Slyne Ridge, to the west by the Porcupine Ridge, to the east by the Irish Mainland Shelf and merges to the southeast with the Goban Spur. The Gollum Channel system in the southeast cuts through the slope with deep E-W oriented canyons (Beyer et al., 2003). The shape of the Seabight is controlled by reactivated, down-to-basement normal faults (Moore and Shannon, 1995), and almost 9 km of sedimentary fill thickening from north to south has been deposited since basin formation.

The Porcupine Seabight: Geological History

The development of the PSB was initiated by rifting in the Mesozoic (Naylor and Anstey, 1987). This produced several small rift basins with continental alluvial, fluvial, red-bed clastic and evaporite deposits (Shannon et al., 1995). Minor rifting and continued subsidence followed in the Late Jurassic, with the deposition of marine shales (Johnston et al., 2001). Continued rifting throughout the Late Jurassic determined the shape of the modern Porcupine Seabight (Shannon, 1991), and sedimentation was variable, with lacustrine and non-marine siliciclastic deposition in the north, (Sinclair, 1995), while the high subsidence rate allowed the development of a marginal marine, muddy shelf system with a high clastic input to develop (Johnston et al., 2001; Robinson and Canham, 2001).

Minor rifting and thermal subsidence of the basin in the Aptian and Albian developed thick overlying marine carbonates and shale deposited in anoxic conditions, with local clastic fans, deltas, turbidite or mass-flow deposits, channel and marine shelf sands (Sinclair, 1995; Johnston et al., 2001). Further uplift occurred at the Palaeocene-Eocene boundary, followed by renewed subsidence in the Early Eocene resulting in enhanced sedimentation in the Porcupine Seabight Basin (Jones et al., 2001). Fully marine deposition was established in the Porcupine Basin by the end of the Albian (Sinclair, 1995).

The Lower Tertiary was a period of lowstand conditions with the development of local deltaic deposits and submarine fans. These sediments are overlain by units deposited in increasing water depths and more tranquil conditions, and mark a transition from carbonate to clastic sedimentation (Shannon et al., 1995). From the Late Eocene to the present, the Porcupine Basin and surrounding margins have been entirely below sealevel (Jones et al., 2001), with the deposition of deltas in the north and submarine fans in the south (McDonnell and Shannon, 2001). Fully marine conditions were also present in the Oligocene and resulted in the deposition of shales and thin limestones (McDonnell and Shannon, 2001). A strengthening of bottom currents in the basin in the Early Miocene is marked by a basin-wide unconformity, and is correlative with events elsewhere in the North Atlantic (McDonnell and Shannon, 2001; Stoker et al., 2002). Further marine shale deposition took place in the middle to Late Miocene. Uplift of continental areas in the Early Pliocene caused changes in the oceanographic conditions in the PSB with the establishment of modern circulation patterns (Stoker et al., 2002). The carbonate mounds growing in the PSB today are based on the regional Early Pliocene unconformity identified in seismic data (McDonnell and Shannon, 2001). Glacial and interglacial events during the Pleistocene have deposited continental material in otherwise marine carbonates (Rice et al., 1990; Rüggeberg et al., in press; Dorschel et al., 2005).

The Porcupine Seabight: Modern Sedimentation

The modern sedimentary regime in the PSB is characterised by a relatively low sediment supply, deep water deposition and no shoreline within the basin (Tate, 1993). Deposition is dominated by pelagic to hemi-pelagic carbonates with low sedimentation rates (Freiwald et al., 2002; Swennen et al., 1998). Modern sediment supply is from the Celtic and Irish shelves, with limited sediment provided by the Porcupine Bank (Rice et al., 1991). The other possible source of sediment, the Gollum Channel system, is thought to be inactive in the present day (Wheeler et al., 1998b).

Reworked foraminiferal sands dominate the eastern margin of the PSB (Rice et al., 1991) and have also been recovered from the northern margin (Rüggeberg et al., submitted; Rüggeberg et al., in press; Dorschel et al., 2005).Carbonate mounds have been identified in 3 regions of the Seabight and are thought to be related to water mass properties and local currents (Hovland and Thomsen, 1997; Henriet et al., 1998; De Mol, 2002; Van Rooij et al., 2003). These will be discussed separately in more detail later.

In the present day the margin is influenced by strong along-slope and turbidity currents, resulting in considerable redistribution of glacial sediments (Rice et al., 1991; De Mol, 2002; Huvenne, 2003; Van Rooij, 2004; Rüggeberg et al., in press). Evidence for the presence of modern drift activity comes from textural analysis of side scan sonar imagery and seismic analysis, with striated and rippled sands and sand sheets and waves identified on the seafloor (Kenyon et al., 1998; Chachkine and Akhmetzhanov et al., 1998; Akhmetzhanov et al., 2001; De Mol, 2002; Huvenne et al., 2002b; Van Rooij et al., 2003; Beyer et al., 2003; Foubert et al., 2005). The volume of sediment transported and re-deposited by these bottom currents is substantial, burying structures several tens of meters in height (Huvenne et al., 2003; Van Rooij, 2004). Small turbidite sequences are predicted to occur on the southeastern margin of the PSB, with some evidence of debris flows (De Mol, 2002; Van Rooij et al., 2003).

The Porcupine Seabight: Oceanographic Regime

Surface waters in the PSB average a temperature of 14-16˚C with a salinity of 35.5 ‰ (White et al., 1998). These values persist to ~ 50 m water depth below which Eastern North Atlantic Water (ENAW) is identifiable by lower salinity and temperatures down to approximately 600 m (Rice et al., 1991; Vermeulen, 1996; White, in press). Mediterranean Outflow Water (MOW), a highly saline and oxygen depleted water-mass occurs below this depth down to 1000 m (Rice et al., 1991; Van Aken, 2000; White, in press). Scatter in data at the boundaries of these water masses has been suggested to be a result of mixing through internal tides (Rice et al., 1991; De Mol et al., 2002; Mohn and Beckmann, 2002).

Currents in the eastern PSB flow in a northerly direction (Rice et al., 1991; Hall and McCave, 1998; White, in press). Measured bottom current speeds from previous work on the eastern margin average a velocity of 4 cm/s between 500 and 1000 m (Pingree and Le Cann, 1989; Pingree and Le Cann, 1990), while calculations of current speed from observed bedforms suggest that velocities may occasionally reach more than 100 cm/s (Akhmetzhanov et al., 2001), which is are supported by video footage of coarse surface sediments (Huvenne et al., 2002a; Foubert et al., 2005). Present-day current speeds are inferred to be highest on the south eastern margin of the basin, due to the combination of the northerly slope current and superimposed internal waves and tides (Davies and Xing, 2001; Mohn and Beckmann, 2002; Mohn et al., 2002; Huvenne et al., 2002a). Localised increases in current speeds are anticipated in the carbonate mound provinces due to current focussing at topographic highs (Trasvina-Castro et al., 2003; Turnewitsch et al., 2004).

Bottom currents in the PSB are thought to have been moulding surface sediments since the Miocene (Van Rooij et al., 2003), and their intensity is suggested as being controlled by the MOW (Schoenfeld, 2002; Loewemark et al., 2004). The influence of MOW on the PSB is reduced during glacial periods, with associated lowered sea levels restricting the volume of MOW flowing from the Mediterranean to the Atlantic through the Straits of Gibraltar (Schoenfeld and Zahn, 2000).

The Porcupine Seabight: Carbonate Mounds

Carbonate mounds have occurred in the geological past from the late Proterozoic to the present day in a variety of settings. Carbonate mounds are not located all over the world's oceans today, suggesting that their occurrence is constrained by local conditions. Their prescence has been attributed to particular conditions such as seeps, diapirism, faults and vents, upwelling and particular isobaths (Monty, 1995; Hovland et al., 1998; Henriet et al., 1998) resulting in groups or clusters of mounds.

The cold-water carbonate mounds on the European North Atlantic margin range from structures less than 1 m to greater than 200 m in height (Freiwald and Henrich, 1997; De Mol et al., 2002; Huvenne et al., 2003; Van Gaever et al., 2004). They have been identified as seafloor expressions from side scan sonar and reflection seismic studies (Berndt et al., 2000; van Weering et al., 2003; De Mol et al., 2002; Huvenne et al., 2002a; Huvenne et al., 2002b; Huvenne et al., 2003; Van Rooij et al., in press). On seismic profiles, the mounds tend to be distinct but low amplitude expressions compared to the surrounding seafloor located above a high amplitude reflector.

The sediment of the carbonate mounds is composed of calcium carbonate, with a minor component of siliciclastic grains (Dorschel et al., in press). Cores through the mounds show intensely bioturbated sediments containing a large amount of bioclastic material sourced from the same organisms observed on the mound surfaces (De Mol et al., 1998; Saoutkine, 1998; Sumida and Kennedy, 1998; Swennen et al., 1998; Mazurenko, 1998; Wilson and Herbon, 1998, Akhmetzanov et al., 1998; De Mol et al., 1999; Mazurenko, 2000; De Mol et al., 2002; Rüggeberg et al., in press; Dorschel et al., 2005). Along the Eastern North Atlantic margin, the cold-water azooxanthellate corals *Lophelia pertusa* and *Madrepora oculata* contribute most of the coarse bioclastic material. The high frequency of unconformities and lack of a continuous isotopic record in recovered cores from the mounds indicates that large volumes of sediment have been removed and this has been related to shifts in the local hydrodynamic regime (Rüggeberg et al., in press; Dorschel et al., 2005).

Along the Atlantic Margin the occurrence of the dominant mound building fauna is apparently constrained by the presence of MOW, which influences temperature, salinity, and the dispersal of larvae to this environment (Freiwald, 2002). In the present day, the corals occur in areas where current speeds are sufficient to prevent the settling of fine particles on their polyps, but not so strong as to cover the colonies with sand and coarser grains, or knock them over (Wilson, 1979; Mikkelsen et al., 1982; Freiwald, 2002; Mortensen et al., 1995; Freiwald and Henrich, 1997; Roberts et al., 2003). A wide variety of other organisms is associated with these corals; polychaetes, foraminifers, bryozoa, brachiopods, molluscs, crustaceans, hydroids and echinoids: often settling on them post mortem and contributing bioclastic material to the surrounding seafloor.

The Cold-Water Corals

The azooxanthellate corals *Lophelia pertusa* and *Madrepora oculata* are the most common corals occurring in the carbonate mounds of the NE Atlantic (Mortensen et al., 1995; Freiwald and Wilson, 1998). These corals are not restricted in their location by the photic zone and have a 'cosmopolitan' distribution wherever other environmental constraints are met. These corals require a hard substrate for larval settlement and colonisation, low local sedimentation rates and low water temperatures (between 4 and 12°C) (Freiwald and Wilson, 1998). Some association of the coral's occurrence has been made with areas of high surface productivity (Frederiksen et al., 1992).

The corals tend to be located on raised substrates such as seafloor outcrops, iceberg plough-marks, hardgrounds or even anthropogenic structures (e.g. pipelines or subsea cables), (Hovland et al., 1998; Freiwald et al., 1999; Bell and Smith, 1999; Freiwald et al., 2002) where they may form dense frameworks. These frameworks range in size from individual corals to small colonies approximately 1 m in height, and range in width from 1.5 to 2 m (Freiwald and Wilson, 1998). As the colonies continue to grow and increase in size, bioeroding organisms attack the bases in the centre of the colony and initiate some collapse of the structure, producing coral rubble. This rubble forms a new substrate for colonisation. As the rubble is colonised and the colonies continue to growth, thickets typically 6-8 m in diameter form and continue to spread until they reach a 'coral patch' stage (Wilson, 1979). The continued cycle of coral settling, growth and rubble formation leads to a final 'coral bank' stage (Teichert, 1958). The baffling of suspended sediments by these structures forms the deep water coral build-ups seen in the NE Atlantic today (Freiwald, 2002). These are characterised as structures with some vertical relief (generally > 1 m) with colonies of living corals on their uppermost flanks (Mortensen et al., 1995). These corals are growing on a framework of dead corals, partially infilled by hemipelagic sediments to form mounded structures (Figure 1.2).

Carbonate Mounds in the Porcupine Seabight

The earliest known occurrence of carbonate mounds in the PSB is from the Late Cretaceous (PK3 sequence of (Moore and Shannon (1995)). These were mounded structures occurring on the basin margins on a carbonate ramp, rooted on calciturbidites or slump masses. These mounds vary in size and shape through the Cretaceous sequence and the authors liken them to mound structures forming elsewhere in Europe at this time. Evidence for strong currents (required for reef building organisms) is supplied by topographic lows cutting into the carbonate

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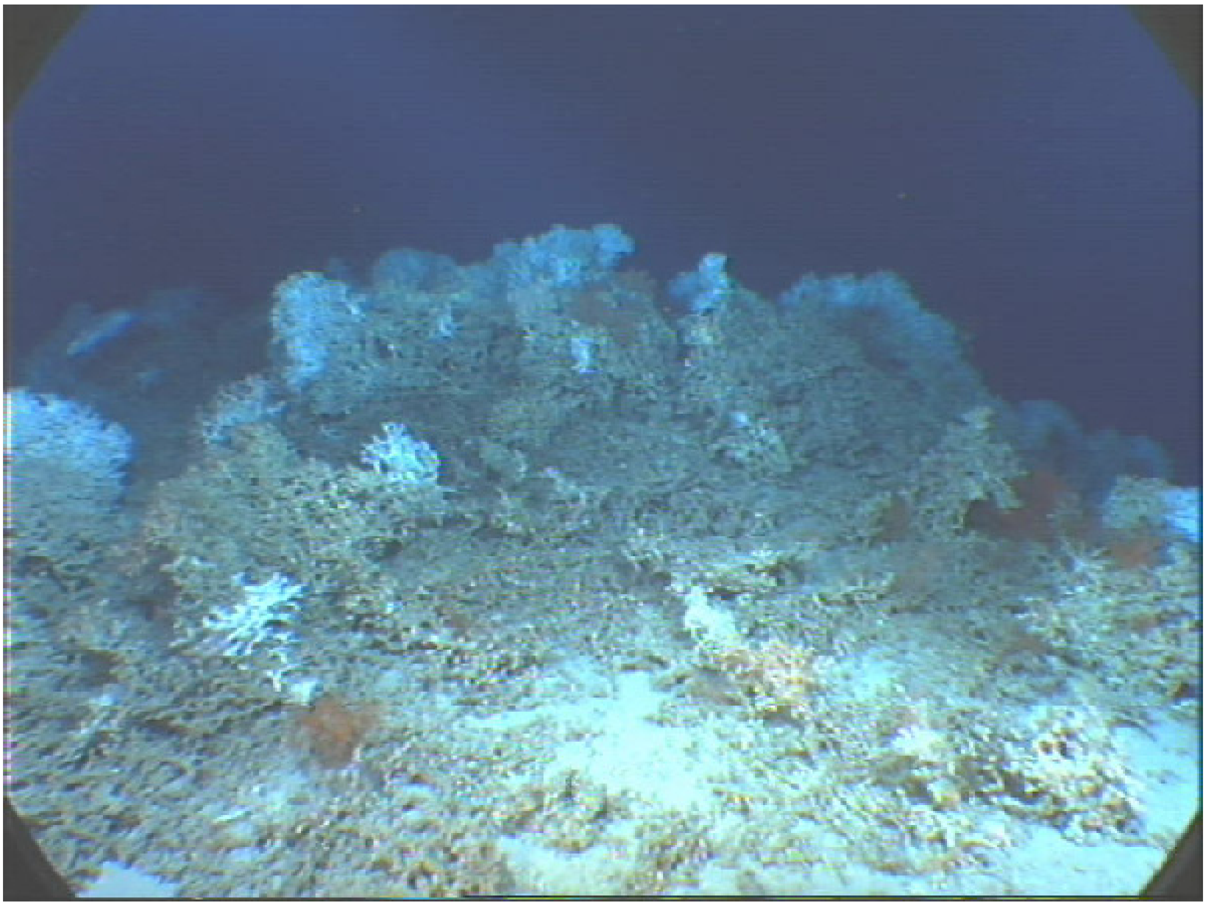

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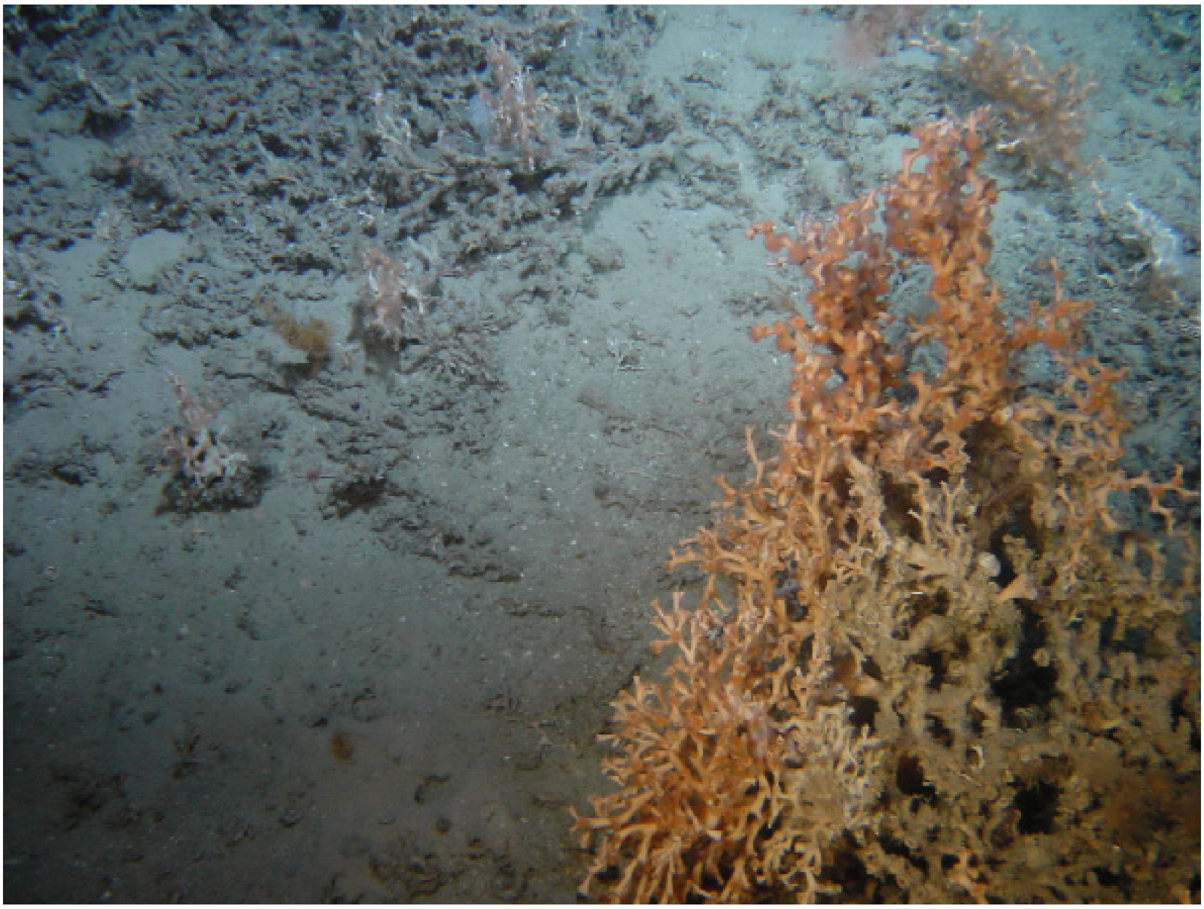

Figure 1.2: Examples of cold water corals on Propeller Mound, Hovland Mound Province. A: Thicket of live coral (white) growing on dead rubble (grey). B: Closer view showing living *Lophelia pertusa* colonising dead rubble partially buried by surface sediments. Both images copyright IFREMER.

sediment forming large channel structures. The Cretaceous mounds were subsequently buried by low energy sediment when conditions were no longer favourable for coral growth.

Today, the PSB supports an active system of carbonate mounds. Like their Late Cretaceous precursors, they are isolated, deep marine biohermal build-ups. They also vary in size and shape, are seated on unconformities, have erosional channels associated with them and in some areas have been buried by – or are being buried by fine grained marine sediment (De Mol et al., 2002; Huvenne et al., 2002a; Dorchel et al., in press; Rüggeberg et al., submitted). It is thought that these mounds share a common initiation period during the Early Pliocene and are all situated on a regional unconformity (McDonnell and Shannon, 2001).

There are three modern carbonate mound ‘provinces’ in the PSB, each displaying particular characteristics (De Mol et al., 2002; Huvenne et al., 2003). Examples of seismic profiles through each mound province are shown in Figure 1.3.

1. Belgica Mound Province (BMP)

This is the most southerly mound province in the PSB, occurring on the south eastern margin of the basin. The mounds are typically high (up to 150 m), with their down-slope side exposed at the seafloor, but uppermost flank almost entirely buried by sediment. Living corals are present in the BMP today.

2. Hovland Mound Province (HMP)

This is the central mound province, and is characterised by large (up to 200 m high) conical mounds or elongate ridges associated with deep moat structures on the seafloor. Estimations of sedimentation rates in this mound province indicate that the mounds are being buried by drift sediments, and coral growth is not as prolific as that in the BMP (Dorschel et al., in press). Propeller Mound, the main focus of this study is located in this province.

3. Magellan Mound Province (MMP)

This is the northernmost mound province in the PSB. It is a densely populated mound province, with more than 1000 small (<100 m) mounds, most of which have been buried by drift sediments (Huvenne et al., 2003). There is some expression of the mounds at the seafloor, as well as limited coral growth (Huvenne et al., 2005).

Propeller Mound – a Hovland Mound

Propeller Mound is the largest carbonate mound in the HMP. It is an asymmetric tri-lobate structure composed of several amalgamated mounds and drift sediments. The crest of the mound is located at 660 m water depth, with a height of 140 m above the seafloor. Analysis of seismic profiles has shown that the mound is approximately 280 m high from crest to base (De Mol et al., 2002), dwarfing surrounding mounds by up to 80 m. Propeller Mound has steep flanks, ranging from about 12° to 60° in inclination. Steepest slopes occur on the western side of the mound, and gentler slopes on the east.

At Propeller Mound, current activity is inferred from the occurrence of dropstone pavements and outcropping hardgrounds (Freiwald and shipboard party, 2002; Dorschel et al., 2005). The mound is bounded by a moat on its western flank which has been attributed to continuous erosion (Freiwald, 2000; De Mol, 2002; Freiwald and shipboard party, 2002; Huvenne et al., 2002a; Van Rooij et al., 2003). A NW – SE trending drift sediment wedge is interpreted from the bathymetric profile to the west of Propeller Mound by Freiwald and shipboard party, (2002).

Carbonate Mound Growth and Development

Carbonate mound growth in the PSB is thought to have initiated at ~5.3 Ma (Ferdelman et al., 2005). All the mounds are set on the same erosional unconformity, suggesting that their initiation was coeval (McDonnell and Shannon, 2001; De Mol, 2002). Furthermore it is likely that their growth was triggered by an instantaneous event providing optimal conditions for the growth of the mound building organisms. Assuming that the corals *Lophelia pertusa* and *Madrepora oculata* were present from the initiation of mound growth through to the present day, several specific

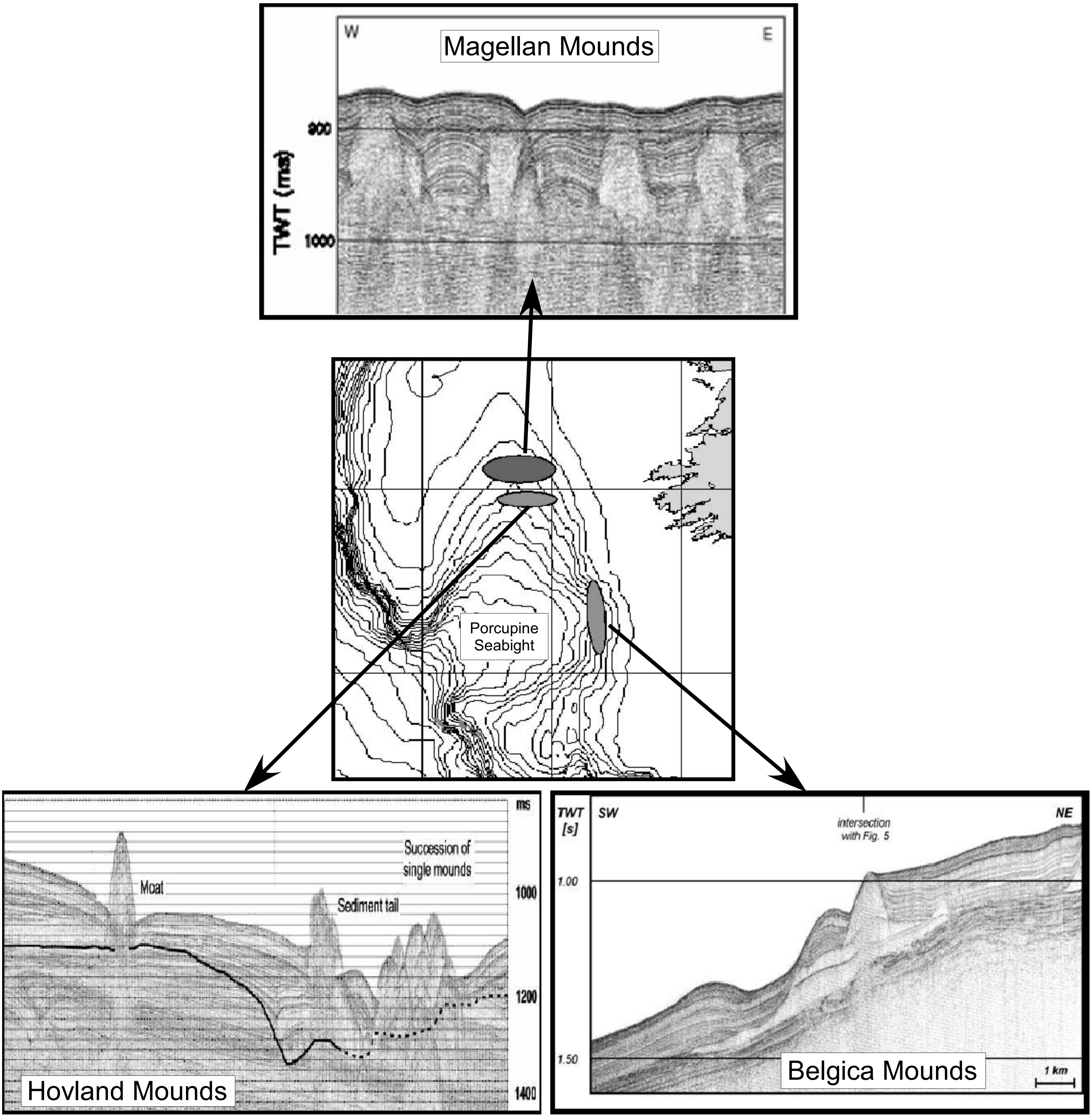

Figure 1.3: Seismic profiles through the 3 carbonate mound provinces in the Porcupine Seabight displaying the major morphological characteristics used in classifying the mounds in these areas. Seismic profiles for Magellan Mounds sourced from Huvenne et al., 2003, Belgica Mounds from Van Rooij et at., 2003 and Hovland Mounds from De Mol et al., 2002.

environmental parameters would have to have been met for this to occur. The mound building corals require a hard substrate for colonisation, the presence of bottom currents to supply food and prevent burial by sediments, and optimal temperature and salinity conditions (Freiwald and Henrich, 1997; Mortensen et al., 2001).

Hovland et al., (1994) suggested that the mounds initiated growth due to chemosynthetic symbiosis of organisms dependant on hydrocarbon seepage along fault planes through to the seafloor, although Henriet et al., (1998) suggested that gas hydrate crystals in seafloor sediment are more likely to have provided an energy source for the colonising organisms. This may have occurred in other locations (e.g. Norway, Hovland et al., 1998; Hovland and Risk, 2003) or in other deep-sea communities (e.g. Gulf of Mexico, MacDonald et al., 2003), however, no conclusive evidence to support this hypothesis for the PSB has been found (De Mol et al., 2002; Ferdelman et al., 2005).

The cause for mound initiation is still unknown and models for mound development have been proposed on the basis of seismic and sedimentological studies. De Mol (2002) and Henriet et al., (2002) suggest a system comparable to tropical reef development, with a trigger stage of initiation, a booster stage of rapid vertical accretion, a coral bank stage of equilibrium with the environment and a final burial stage where the mounds are overwhelmed by the surrounding sediment. In addition, Rüggeberg et al., (in press) and Dorschel et al., (2005) have identified a dependence between growth and erosion of the mounds in the PSB and glacial and interglacial cycles. In both studies coral growth is predicted to stop during glaciations due to cooler temperatures, high sediment supply and lowered bottom current speeds, while erosion and winnowing of sediment follows during transitions to interglacials. Resettlement of the mounds and vertical growth is most pronounced during interstadials.

CHAPTER 2: Materials and Methods

SEDIMENT CORE TREATMENT

This thesis studied 1 piston core, 5 gravity cores and 13 box cores retrieved from the flank of Challenger Mound in the Belgica Mound Province and from Propeller Mound and the surrounding seafloor in the Hovland Mound Province (Table 2.1). These were collected during cruises POS-292, POS-265, M61/3 and MD-123 Geosciences Leg 2 on board the *R/V Poseidon, R/V Meteor* and *R/V Marion Dufresne* respectively (Freiwald and shipboard party, 2000; Freiwald and shipboard party, 2002; Ratmeyer et al., 2004; Van Rooij et al., 2001). Additional references are made to data acquired from gravity cores analysed by Dorschel et al., 2005. The gravity cores taken by *R/V Poseidon* and *R/V Meteor* (GeoB cores) were cut into one meter sections, whereas the piston and gravity cores from the *R/V Marion Dufresne* (MD-cores) were cut into 1.5 m sections. Both types of core were split into working and archive halves and all cores are stored at 4˚C for further analysis and treatment at the core repository at the University of Bremen.

All data acquired from the cores by instrumental analysis is accessible from the PANGEA data base (http//pangea.de).

Opening procedure of cores

Conventional opening procedures were applied to off-mound cores at the University of Bremen. On-mound cores were given special attention due to the disturbance of the sediment by large bioclasts. The on-mound cores were first frozen at -18˚C for 72 hours before being cut with a diamond bladed rock saw. Immediately after cutting, the frozen cutting fluid and upper surface of the core halves were removed with a knife to preserve sedimentological structures without significant damage.

Visual core descriptions

All gravity and piston core sections were visually described after opening, with sedimentary structures, lithological contacts and fossils, coring disturbance and colour changes noted. On-mound cores typically contain large bioclasts dominated by the azooxanthellate corals *Lophelia pertusa* and *Madrepora oculata* in a matrix composed of foraminifera, coccoliths and terrigenous material. Preservation of bioclastic material is variable along the length of the cores. Off-mound cores are dominated by hemi-pelagic material, with few large bioclasts. Large lithic fragments are encountered at some depths, and the majority of sediment is composed of silty sands.

Box core surfaces were first photographed before a description was made of the biota, carbonate and siliciclastic grain size and type, and sedimentary structures. This was carried out on deck immediately after recovery. As for the gravity cores, on-mound cores contained significant quantities of bioclastic material, and off-mound cores were dominated by hemi-pelagic sediment with lithic fragments present.

Subsampling

Box–core sampling was carried out immediately after recovery. 10 cm^2 sub-samples of the uppermost 0.5 cm were then taken for grain size analysis, grain identification, and total organic carbon (TOC) and calcium carbonate content measurements.

Gravity and piston cores were sub-sampled with 10 cm^3 syringes with the exception of MD-01-2460G which was sub-sampled with a hammer at 10 cm intervals due to the desiccation of the core during storage. Sub-samples were collected for grain size, grain type, isotopic and stratigraphic analyses. All samples were weighed and freeze dried at -50˚C. Sampling intervals for the GEOB cores were at 5 cm, and at 10 cm for the MD cores. Higher sampling densities were used in areas of rapid textural or compositional change for all core types.

A sub-sample set was wet sieved at 63 µm and 125 µm, and used for isotopic analysis and dating. The > 125 µm fraction was also described using a binocular microscope at x10 magnification to identify grain types. Samples for bulk analysis were ground and homogenised using an agate mortar.

Location	Core Type	Core No.	Latitude	Longitude	Water Depth (m)	Recovery (cm)
Hovland Mound Province	Box Core	GEOB 8059-1	52 09.20N	12 46.88W	804	32
		GEOB 8073-1	52 08.75N	12 47.11W	761	37
		GEOB 6718-1	52 09.58N	12 44.10W	890	27
		GEOB 9245-1	52 08.84N	12 47.14W	769	40
		GEOB 8074-1	52 08.43N	12 45.88W	784	26
		GEOB 8047-1	52 09.34N	12 46.40W	795	23
		GEOB 8040-1	52 08.52N	12 45.30W	809	22
		GEOB 6708-1	52 09.25N	12 46.19W	742	31
		GEOB 6721-1	52 09.22N	12 46.31W	696	22
		GEOB 8045-1	52 09.17N	12 46.13W	682	30
		GEOB 6717-1	52 09.10N	12 46.23W	686	surface
		GEOB 9246-3	52 08.99N	12 46.20W	750	24
		GEOB 8039-1	52 08.19N	12 46.09W	850	24
	Gravity Core	GEOB 8069-1	52 09.40N	12 46.87W	777	382
		GEOB 8070-1	52 08.79N	12 47.21W	760	447
		GEOB 8071-1	52 08.48N	12 46.05W	761	575
		MD-01-2460G	52 08.97N	12 46.22W	710	1380
Belgica Mound Province	Calypso Core	MD-01-2450	51 22.52N	11 43.81W	944	1196

Table 2.1: Overview of cores used in this thesis

SAMPLE ANALYSIS

Petrographic description/grain type analysis

A total of 389 sub-samples of the >125 µm fraction was described using a binocular microscope at x10 magnification with a visual estimate made of % quartz and lithic fragments, planktic and benthic foraminifera as well as the occurrence of other biogenic grains. Large rock fragments recovered from the box cores were used to aid lithic and mineral identification. This semi-quantitative analysis was used to identify processes that occur during deposition through an interpretation of the occurrence of particular components, and to correlate with data retrieved from other analyses.

Stable Isotope Analysis

Oxygen and carbon isotopic measurements were made on ~5 specimens of 2 benthic foraminiferal species: *Cibicides wuellerstorfi* and *Cibicides kullenbergi* selected from the >125 µm size fraction. For the GEOB cores 8069-1, 8071-1 and 8070-1 this was done at 5 cm intervals, with a higher sampling density taken at well defined lithological boundaries. For cores MD-01-2450 and MD01-2460G a 10 cm sampling interval was applied. A lack of benthic foraminifera below ~6 m depth in core MD-01-2450 resulted in an incomplete record, hence a second suite of 10 to 40 specimens of the planktic foraminifer *Neoglobigerina pachyderma* were picked for analysis.

Determinations were made using a Finnigan MAT 251 mass spectrometer. The isotopic composition of the carbonate sample was measured on the CO_2 gas evolved by treatment with phosphoric acid at a constant temperature of 75ºC. For all stable isotope measurements a working standard (Burgbrohl CO_2 Gas) was used, which had been calibrated against PDB by using NBS 18, 19 and 20 standards. Consequently all $\delta^{18}O$ and $\delta^{13}C$ data given here are relative to the PDB standard. Analytical standard deviation is about +/- 0.07 % PDB for $\delta^{18}O$ and +/- 0.05 % PDB for $\delta^{13}C$ (Isotope Lab Bremen University). References to isotopic values for the GEOB cores 6728-1, 6729-1 and 6730-1 in Chapter 5 are derived from Dorschel et al. (2005).

DATING

Radiocarbon measurements

Accelerator Mass Spectrometry (AMS) ^{14}C dating was carried out on mono-specific samples (9 – 12 mg) of the planktic foraminifer *Neogloboquadrina pachyderma* (either dextral or sinistral) picked from the >125 µm fraction of MD-01-2450. Ages were determined at the Leibniz Laboratory for Age Determination and Isotope Research at the University of Kiel (Nadeau et al., 1997). All AMS ^{14}C ages were corrected for ^{13}C and calibrated to kilo-years before present (kyr B.P.) using CalPal (Weninger et al., 2004).

Coccolith biostratigraphy

Coccolith biostratigraphy was applied to sediments older than those within the range of radiocarbon dating. In MD-01-2450 this was below 6 m in depth and samples were taken every meter. Dissolution of carbonate at these depths along the core resulted in only one approximate age being identified. For core MD-01-2460G areas for biostratigraphic dating were identified on the basis of lithological change. Analyses were carried out by Dr. K.H. Baumann at the University of Bremen. A detailed description is given in Chapter 5.

For preparation of coccolith samples a combined dilution/filtering technique as described by Andruleit, 1996 was used. A sediment sample (about 60 mg) was brought into suspension and further diluted with a rotary splitter. The suspension was filtered onto polycarbonate membrane filters (Schleicher & Schuell™, 0.4 µm pore size) and dried in an oven at 40°C. A small piece of the filter (1x1 cm) was cut out and mounted onto an aluminium stub. Coccoliths were searched for by means of a scanning electron microscope (SEM) at a magnification of 2000x or 3000x. At least 200 specimens were counted for each sample in order to determine their relative abundances and their stratigraphic changes.

U/TH dating on coral fragments

Fragments of the coral *Lophelia pertusa* were taken from several depths of MD-01-2460G (141, 396, 725, 930, 1177, 1345 cm). However the aragonite skeletons were found to be in advanced stages of dissolution either due to extended periods of exposure at the seafloor or due to their age (postulated they were more than 0.3 Ma old) and no dates were able to be recovered from them. No data from these samples exist for the pangea database.

TOTAL ORGANIC CARBON AND $CaCO_3$ CONTENTS

These analyses were conducted on box core surface samples only. To determine total carbon (TC) content, analyses on 25 mg of sub-sample for each location were performed on a Heraeus-CHN-elementary analyser . In subsequent analyses, samples were pre-treated with HCl to remove calcium carbonate and dried on a hotplate at 80ºC to determine the total organic carbon (TOC) content. The bulk carbonate percentage (% $CaCO_3$) was then calculated from the TC content of the sediment measured with the CHN analyser on untreated samples using the equation:

$CaCO_3$ % = (TC % - TOC %) x 8.33

X-RAY FLOURESCENCE SPECTROMETRY (XRF)

Elemental composition of all the cores was determined using the CORTEX-XRF scanner at the ODP core repository, Bremen. For GEOB cores scans were run for 30 counts at 20 kV with 5 cm spacing along the whole length of split core apart from at depths of high coral concentration which prevented measurement. In these incidences, a measurement was made as closely as possible to the original depth. For core MD-01-2450 measurements were made at a 5 cm sampling interval, then re-run at a 1 cm interval for the uppermost 6 m to delineate higher frequency fluctuations in this section.

The data were processed using Toolbox, the associated Kevex software, and yielded curves for the elements K, Ca, Ti, Mn, Fe, Cu, Sr, V, Cr, Co, Ni, Zn, and Pb. In our study we have referred only to the Ca and Fe curves. The Ca curve was used as an indication for total $CaCO_3$ in the core, and Fe as a proxy for the influx of terrigenous material (Paelike et al., 2001). Results are presented as percentages of the total element counts (% TC). This normalizing procedure reduces noise levels and largely avoids artifacts related to variations in grain-size distribution and surface roughness.

GRAIN SIZE ANALYSES

Box Core grain size analyses

Particle size analysis was performed using a Coulter LS2000 on all the surface samples over a size range from 0.375 – 2000 µm. Samples were first treated to remove excess salt by washing, mechanical agitation and settling undisturbed for several days. This resulted in grains layered according to size fraction. The samples were then freeze dried before subdivision to obtain a smaller sub-sample with all grain sizes represented. Two sample sets were prepared by sieving a few milligrams of bulk sediment over a 2000 µm sieve directly into a glass chamber where they were mechanically dispersed with water. Organic carbon, carbonate and biogenic opal were removed prior to the grain size analysis by treatment with excess H_2O_2, HCl, and NaOH respectively for one sample set. The second sample set was untreated and was also measured to enable a calculation of siliciclastic and carbonate grain size distribution. From the raw data the grain size distribution of the different size fractions were calculated and they are presented as % volume of sediment. Testing of several sub-samples was done until samples yielded similar results, indicating that the results were robust to the processing steps.

Gravity Core Analysis

Coulter LS2000

Grain size distribution curves for MD-01-2460G were determined using a Coulter LS2000 using a 10 cm sampling interval along the length of the 13.8 m long core. Analyses were run on carbonate free sediment in the size range from 0.375 – 2000 µm only. Samples were prepared from several mg of freeze dried bulk sediment sieved through a 2000 µm mesh. This sediment was mechanically dispersed in water before treatment with excess H_2O_2 to remove organic carbon, HCl to remove carbonate and

NaOH to remove biogenic silica. Analyses were repeated several times to establish repeatability before statistical calculations of the different grain size classes.

Malvern Laser Particle Sizer Mastersizer 2000

Particle size analyses were performed on samples from MD-01-2450 using the Malvern Laser Particle Sizer Mastersizer 2000 by M. Kozachenko at the Coastal and Marine Resources Centre, University College of Cork, Ireland. A sampling interval of 10 cm was used, with a higher density taken in areas of rapid lithological change. Representative sub-samples were taken for analysis with each sub-sample dispersed in 10% sodium polyphosphate solution made with distilled water and shaken for 24 hours with an automatic flask shaker in order to achieve a perfect dispersion of all particles within the sample. All sub-samples were sieved and only the fraction < 2 mm (2000 µm) was used for analysis. Each sub-sample was measured 5-10 times and the average result taken to represent the sample.

Particle size distributions were statistically analysed to produce the following variables: percentage clay (% < 2 µm), percentage silt (% 2-63 µm), percentage sortable silt (% 10-63 µm), percentage sand (% 63-2000 µm), IRD index (% > 150 µm) and mean sortable silt size.

CHAPTER 3: Glaciomarine drift sedimentation and bottom current variability: Belgica Mound Province, Porcupine Seabight

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Keywords: Belgica Mounds, drift, glaciomarine, Porcupine Seabight

ABSTRACT

Lithological, grain size, isotopic and geochemical studies have been conducted on an 11.75 m long core recovered from the Porcupine Seabight off the coast of south western Ireland. The sedimentary record covers parts of the last glacial (~35 kyr B.P. to ~21 kyr B.P. with an average sedimentation rate of ~38 cm/kyr) and an older, underlying section (>200 kyr. B.P.), separated by a hiatus. The lower part of the core provides evidence of an older glacial period, with significantly reduced water mass ventilation and an absence of coarse ice rafted debris, while the upper section has higher average grain sizes and calcium carbonate contents. The results of grain size analysis along the core indicate that sedimentation was affected by bottom current activity, with variation in current speed and sediment supply through time.

INTRODUCTION

In addition to the vertical particle flux through the water column continental margins are commonly affected by both downslope and alongslope sediment transport processes. Sediment can be supplied by debris or turbidity flows and later on gradually reworked into drift bodies by bottom current activity. The composition of the drift reflects the regional setting and may be used to infer syn-depositional processes, while changes in the sediment grain size may reflect variations in bottom current intensity. Bottom currents are extremely size selective in terms of erosion as well as deposition (McCave et al., 1995; Weltje and Prins, 2003) and transported grains are typically <60 µm (Prins et al., 2002; Weltje and Prins, 2003).

The Porcupine Seabight (PSB) is thought to have been a site of active bottom current flow since the Miocene, with the erosion of channels and formation of drift bodies interpreted from seismic profiles (Van Rooij et al., 2003). Bottom current activity in the PSB today is postulated to be driven by the Mediterranean Outflow Water (MOW), a highly saline and oxygen depleted water mass (Schoenfeld, 2002b; Loewemark et al., 2004). Lowered sealevels during glacial periods are thought to have restricted the flow of MOW from the Mediterranean to the Atlantic through the Straits of Gibraltar (Schoenfeld and Zahn, 2000). Some of the effects of this in the PSB are discussed by (Dorschel et al., in press; Rüggeberg et al., in press).

Previous studies in the PSB have concentrated predominantly on the distribution and biology of the carbonate mounds on the seafloor (Rice et al., 1991; Hovland et al., 1994; Henriet et al., 1998; Freiwald et al., 1999; De Mol et al., 2002; Huvenne et al., 2003). Some have suggested a relationship between the occurrence of these mounds and the activity of bottom currents and the presence of the MOW (Rice et al., 1991; Freiwald et al., 1999; Van Rooij, 2004; Dorschel et al., in press; Rüggeberg et al., in press).

Understanding how significant the variability in current intensity has been through glacial/interglacial events and what changes have occurred in sediment supply and accumulation during these times may provide some insight to the factors determining the location of such carbonate mounds in the PSB. This paper aims to describe sediment accumulating in a carbonate mound province and to interpret processes having operated in the PSB during the Late Pleistocene from the sedimentary record.

REGIONAL SETTING

Physiography

The PSB (Figure 3.1) occurs off the west coast of Ireland. It is a NE-SW oriented sedimentary basin formed in the Mid- to Late Jurassic on a failed rift (Shannon, 1991). The modern PSB is approximately 150 km long and varies in width from 65 km in the north to 100 km in the south. Its bathymetric depth increases from 300 m in the north to over 2000 m in the south. The PSB is bound by three shallow platforms: the Slyne Ridge in the north, the Irish Mainland Shelf to the east and the Porcupine Ridge in the west (Croker and Shannon, 1995) .

Present day bottom-water circulation

Two main water masses can be recognised in the study area today: Eastern North Atlantic Water occurs below the surface current down to a core of minimum salinity between 500-600 m depth, below which highly saline MOW is found from 800 to 1000 m (Rice et al., 1991; Van Aken, 2000; White, in press). Scatter in data at the boundaries of these water masses has been suggested as a result of mixing through internal tides, (Rice et al., 1991; De Mol et al., 2002; Mohn and Beckmann, 2002). The results of hydrodynamic modelling and current meter deployment indicate that currents in the PSB generally flow in a northerly direction long the eastern margin (Rice et al., 1991; White, 2001; Hall and McCave, 1998). Measured current speeds average 4 cm/s between 500 and 1000 m water depth (Pingree and Le Cann, 1989; Pingree and Le Cann, 1990). However, higher current speeds of up to 100 cm/s have been inferred from calculations based on the geometry and scale of observed bedforms (Akhmetzhanov et al., 2001) and from the coarseness of the sediment surface texture observed in side scan sonar and sea floor images (Huvenne et al., 2002a; Foubert et al., 2005). The northerly slope current is likely to be affected by internal waves and tides in the Seabight, resulting in an increase in current velocities locally (Mohn and Beckmann, 2002; Mohn et al., 2002; Huvenne et al., 2002a). The effects of this would be highest in the south eastern flank of the basin.

Sedimentation

The influx of terrigenous material to the PSB today is low (Tate, 1993), and is likely to have a provenance from the Irish and Celtic shelves, with a limited contribution from the Porcupine Bank (Rice et al., 1991). The Gollum Channel system in the south of the PSB is thought to be inactive today, although it may have transported sediment to the southeast of the basin in the past (Wheeler et al., 1998b).

Reworking of sediments by bottom currents has been discussed by Van Rooij et al. (2003) through the identification of drift bodies in seismic profiles. This concurs with observations made during core and sediment analyses in which reworked foraminiferal sands have been recovered (Rice et al., 1991; Rüggeberg et al., submitted; Rüggeberg et al., in press; Dorschel et al., in press), and with analyses of other seismic and side scan sonar data sets (Kenyon et al., 1998; Akhmetzhanov et al., 2001; De Mol, 2002; Huvenne et al., 2002b Van Rooij et al., 2003; Beyer et al., 2003; Foubert et al., 2005).

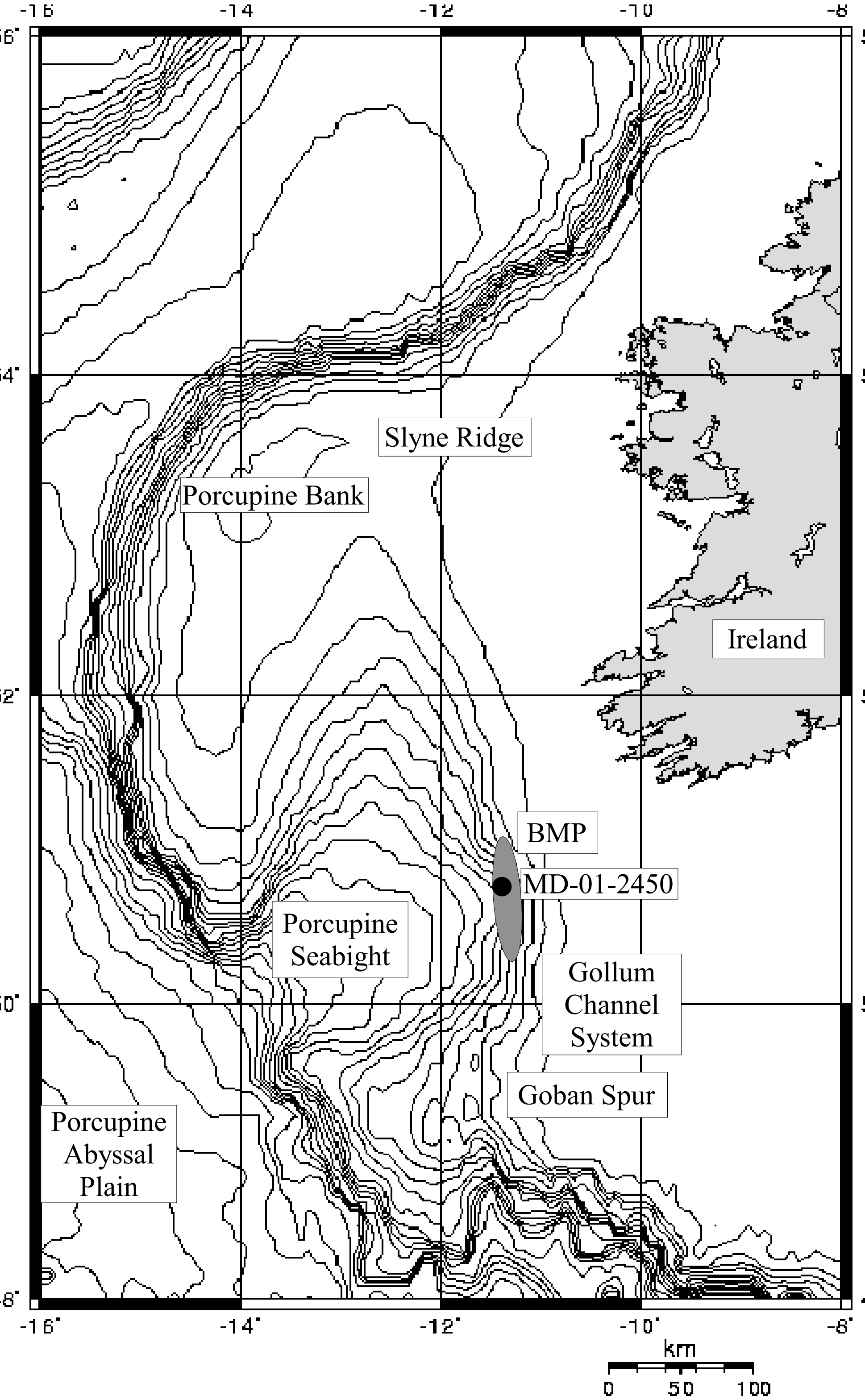

Figure 3.1: Location of the Porcupine Seabight on the European North Atlantic margin, southwest of Ireland. Also shown are the location of the Belgica Mound Province (BMP) and core MD-01-2450.

Three carbonate mound provinces occur within the PSB (Hovland et al., 1994; De Mol et al., 2002), and these mounds contribute some coarse bioclastic material to the seafloor in their immediate surroundings (Dorschel et al., in press; Rüggeberg et al., in press). The core in this study samples the seafloor in the Belgica Mound Province in the southeast of the PSB.

DATA AND METHODS

All the samples analysed here were obtained from core MD-01-2450, a piston core retrieved on R/V *Marion Dufresne* Cruise MD 123-Geosciences, Leg 2, 2001. The core is 11.75 m long and was taken from 944 m water depth at 51°22,5'N and 11°43,8'W. The core was logged descriptively before sub-sampling with syringes for grain size, isotopic and stratigraphic analyses. Samples were taken at 10 cm intervals from 5 cm onwards, with additional samples taken for grain size analysis in areas of rapid textural change. Sub-samples were wet sieved at 63 µm and 125 µm, and used for isotopic analysis and dating. The >125 µm fraction was also described using a binocular microscope at x10 magnification to identify grain types and the occurrence of foraminifera.

The age model for core MD-01-2450 is based on 6 Accelerator Mass Spectrometry (AMS) ^{14}C ages determined from 9 – 12 mg samples of *Neoglobigerina pachyderma* from the grain size fraction >125 µm. Analyses were performed at the Leibniz Laboratory for Age Determination and Isotope Research at the University of Kiel (Nadeau et al., 1997). A correction for ^{13}C was applied and corrected ages were translated to calendar years using CalPal (Weninger et al., 2004). Additional stratigraphic information was provided from coccolith biostratigraphy.

Stable isotope measurements were made at the University of Bremen Isotope Laboratory (Germany) on a Finnigan MAT 251 mass spectrometer. The measurements were performed on either 5 specimens of *Cibicides wuellerstorfi,* 5 specimens of *Cibicides kullenbergi*, or 20 specimens of *Neogloboquadrina pachyderma*. Acid temperature was maintained at 75ºC during analysis. The standard deviation of the isotope values calibrated against PDB by using carbonate standards NBS 18, 19 and 20 is +/- 0.07 % PDB for $\delta^{18}O$ and +/- 0.05 % PDB for $\delta^{13}C$.

A Malvern Laser Particle Sizer (Mastersizer 2000) was used to compare the grain size distribution of the sediment contained in the core. Grain size analyses were performed on bulk sediment at 10 cm intervals for the complete core and at a higher resolution across textural boundaries. Samples were dispersed in 10% sodium polyphosphate solution prepared using distilled water. The suspension was agitated for 24 hours after which it was sieved and the <2000 μm fraction taken for analysis. Measurements were repeated 5-10 times and the results averaged before subdivision into the following grain size classes: clay (% < 2 μm), silt (% 2-63 μm), sortable silt (%10-63 μm), sand (% 63-2000 μm), ice rafted detritus (IRD) index (% > 150 μm) and mean sortable silt size. A low incidence of foraminifera throughout most of the core meant that the size range >150 μm could be used as an indicator of IRD.

Ca and Fe elemental composition of MD-01-2450 was obtained by a non-destructive XRF (X-Ray Fluorescence) scanner (Jansen et al., 1998) using a 30 s count time and 20 kV. The entire core was scanned using a 5 cm interval, and the uppermost 6 m were rescanned at 1 cm spacing for a higher frequency record. The recorded spectrum was analysed using the KEVEX™ software, Toolbox©. The percentage of Ca and Fe are used as indicators of the relative contribution of marine $CaCO_3$ and terrigenous material respectively (Pälike et al., 2001), and are displayed as a percentage of total counts (%TC).

RESULTS

Using stable isotope data, XRF analyses and particle size curves, the core can be divided into 3 lithofacies (Units 1-3) based on lithology, bioturbation, internal structures and texture. Although Units 1 and 3 are composed of a mixture of sand, silt and clay, a distinction is made between them on the basis of the Ca and Fe curves, the sand content and the $\delta^{13}C$ curve. Unit 2 is lithologically distinct from the over and underlying units.

The age dating for the uppermost section (0 - 515 cm) of the core revealed a continuous sequence of six calibrated AMS ^{14}C ages ranging from 34.4 kyr B.P at 515 cm to 21.3 kyr B.P. at 15 cm (Table 3.1). Thus, this part of the core represents parts of marine isotope stages (MIS) 2 and 3. Beneath Unit 2 the sediments were too old to be dated by the radiocarbon method, but the coccolith assemblage points to an age of more than 200 kyr B.P.

Unit 1 (0 – 532 cm): homogenous sandy mud

This unit is composed of a poorly sorted olive grey sandy clayey silt (Figure 3.2) with 37 – 80 % silt, 5 – 23 % sand and 8 – 16 % clay. Its IRD content ranges between 0.8 % and 35 % with values mostly >10 %. Sortable silt values average 32%, with a maximum of 44 % and minimum of 18 %. The average mean sortable silt size is highest in this unit, with a value of 28 μm and a range in size from 25 to 32 μm (Figure 3.3). No sedimentary layering is apparent, and bioturbation is indicated by mottling and homogenisation of the sediment. Smear slides indicate that quartz is extremely common, with lithic clasts, including limestone fragments present. Foraminifera and bioclastic debris also occur, and are noticeably more prevalent than in underlying Unit 3, particularly agglutinating benthic foraminifera. Sulphide nodules occur as sand sized grains and are less common, and much smaller than those of Unit 3. Ca values are between 12 and 26 %TC, and Fe shows higher values from 33 to 41 %TC. Planktic $\delta^{18}O$ data fluctuate between 2.88 and 4.17 ‰PDB, and as in Unit 2, $\delta^{13}C$ values have a considerably higher average than in Unit 3, ranging between – 0.69 and 0.17 ‰ PDB (Figure 3.4). Benthic foraminifer values show fewer fluctuations, with $\delta^{18}O$ ranging from 3.2 to 3.9 ‰PDB, and $\delta^{13}C$ ranging from 0.8 to 1.3 ‰PDB.

Unit 2 (518-532 cm): poorly sorted silty sands

This is the thinnest unit in the core and is composed of very poorly sorted olive brown to yellowish ochre brown stacked sequences of sediment grading from clayey silty sand to clayey sandy silt (Figure 3.2). There is no indication of bioturbation. Particle size curves indicate a high proportion of IRD (44 %), up to 16 % sand, 35 – 43 % silt and minor amounts of clay (7 – 14 %). Sortable silt averages 19.7%, ranging from a maximum of 16 to 24%. Average mean sortable silt size is 27 μm, with a range from 25-29 μm (Figure 3.3). Smear slides show a predominance of quartz grains, with some lithic clasts as well as a high proportion of planktic and benthic foraminifera and comminuted shell debris. Diversity in foraminiferal species is high, particularly in benthic specimens. Ca values range between 13 – 26 %TC and Fe is slightly higher at 33 – 39 %TC. The $\delta^{18}O$ values of *N. pachyderma* vary within a narrow range between 3.4 and 3.44 ‰ and benthic $\delta^{18}O$ values range between 2.4 and 3.4 ‰ PDB. A very prominent signal is displayed by the $\delta^{13}C$ values of *N. pachyderma* marked by a sharp increase from -0.9 ‰ PDB at the top of Unit 3 to 0.19 ‰ PDB within Unit 2 (Figure 3.4). Benthic $\delta^{13}C$ values are fairly constant at about 1.2 ‰ PDB. The contact with Unit 1 is gradational.

Unit 3 (532-1180 cm): moderately well sorted sandy clayey silt

Unit 3 is composed of an olive grey clayey silt to sandy clayey silt with some sections of faint varve-like alternating silt- and clay- rich laminae on a millimetre scale. Throughout the unit there are sulphidic laminae and nodular sulphides up to 12 mm in diameter (Figure 3.2). Bioturbation is rare, but where present it is intense and has almost totally homogenised the sediment. Particle size curves reveal 54 – 80 % silt, a smaller component of clay (<30 %), up to 24 % sand, and between 0% and 10 % IRD (Figure 3.3). Sortable silt averages 30.7 %, although values range from 14 to 42 %. From bulk analyses, mean sortable silt size averages 24 µm, and ranges from 19 to 31 µm. Smear slides indicate that this unit is almost devoid of biogenic grains, and is dominated by quartz and lithic particles. Benthic foraminifera are almost entirely absent, with trace occurrence of planktic specimens. The diversity of species is low, but increases gradually towards the boundary with Unit 2. The Ca values are < 25 %TC, whereas the Fe counts are higher with a lower variability (35 – 42 %TC). $\delta^{18}O$ values for the planktic foraminifera *N. pachyderma* fluctuate between 3.22 - 4.31 ‰ PDB, whereas the respective values for $\delta^{13}C$ show are between -0.98 and -0.28 ‰ PDB (Figure 3.4). Almost all data sets show some variability with similar values at the base of the core and close to the boundary to Unit 2. The contact with the overlying Unit 2 is sharp and erosional.

DISCUSSION

A subdivision of the core into units allows the examination of the processes having occurred at the seafloor of the PSB during parts of the Late Pleistocene. The variation

Core Depth (cm)	AMS ^{14}C age (yr BP)	$\delta^{13}C$ (‰)	Calibrated Age (cal yr BP)	Biostratigraphic Age (yr BP)	LSR (cm/ky)
15	18 450 ± 165	-1.6 ± 0.34	21 340 ± 380		
115	18 780 ± 165	-2.27 ± 0.09	21 640 ± 260		333.33
215	20 340 ± 185	-1.95 ± 0.08	23 610 ± 240		50.76
345	21 990 ± 215	-0.78 ± 0.09	24 830 ± 480		106.56
425	22 600 ± 245	-2.89 ± 0.27	25 800 ± 420		82.47
515	30 670 ± 590	-1.85 ± 0.28	34 440 ± 620		10.42
545	>45 900	-1.81 ± 0.37	>45 840		
600				> 200 000	
635	>45 900	3.13 ±0.18	>45 900		

Table 3.1: ^{14}C and biostratigraphic ages for core MD-01-2450. Values corrected for a reservoir effect of 400 yr and calibrated using the CalPal software of Weninger, 2004. (LSR= Linear sedimentation rate)

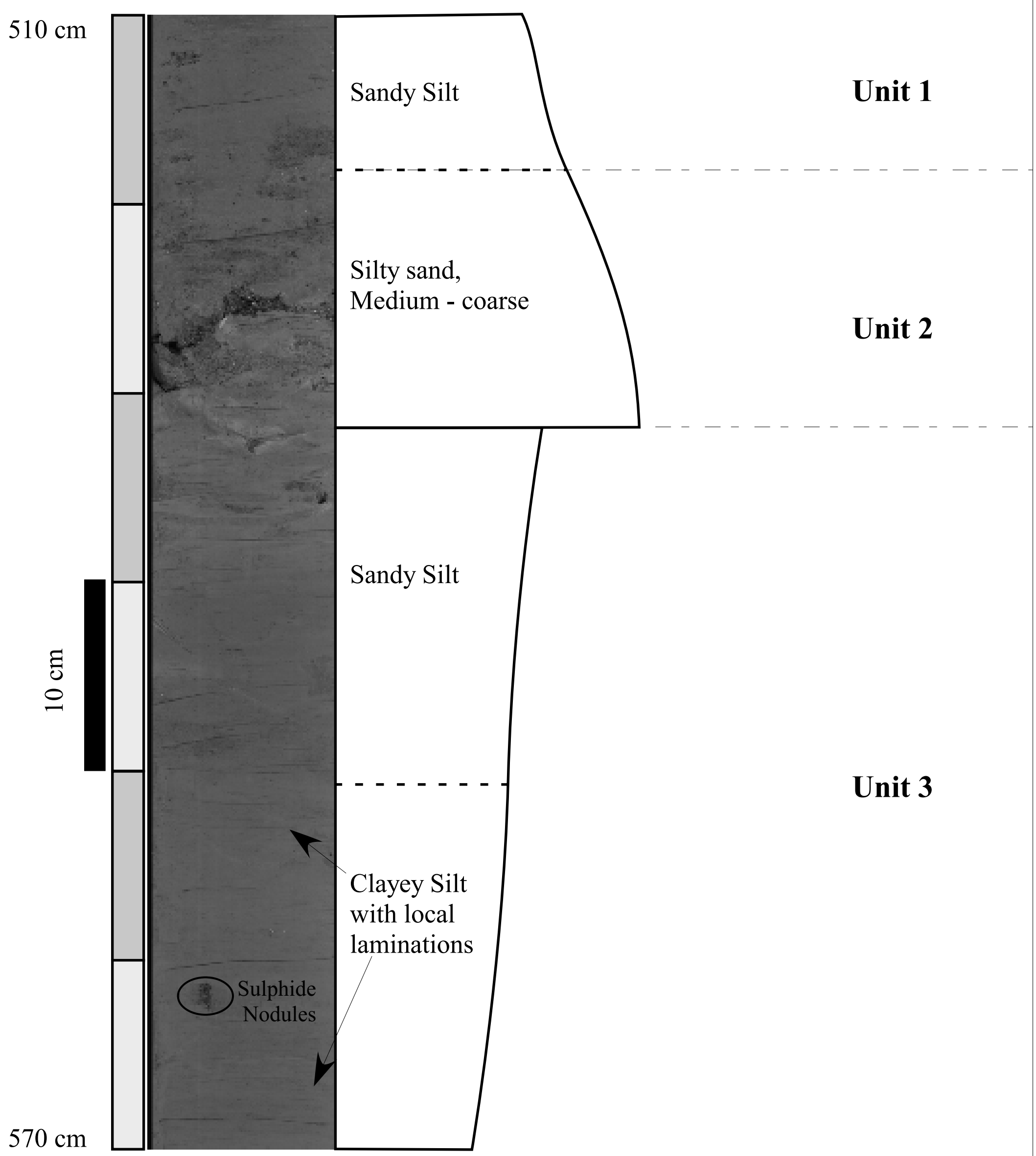

Figure 3.2: Detail of the lithological section from 510 - 570 cm depth in core MD-01-2450 illustrating the coarse grained debris flow sediments of Unit 2. Unit 3 grades from a clayey silt to a fine sandy silt towards the unconformity with Unit 2. The boundary between Units 1 and 2 is diffuse, but is marked by a finer grain size.

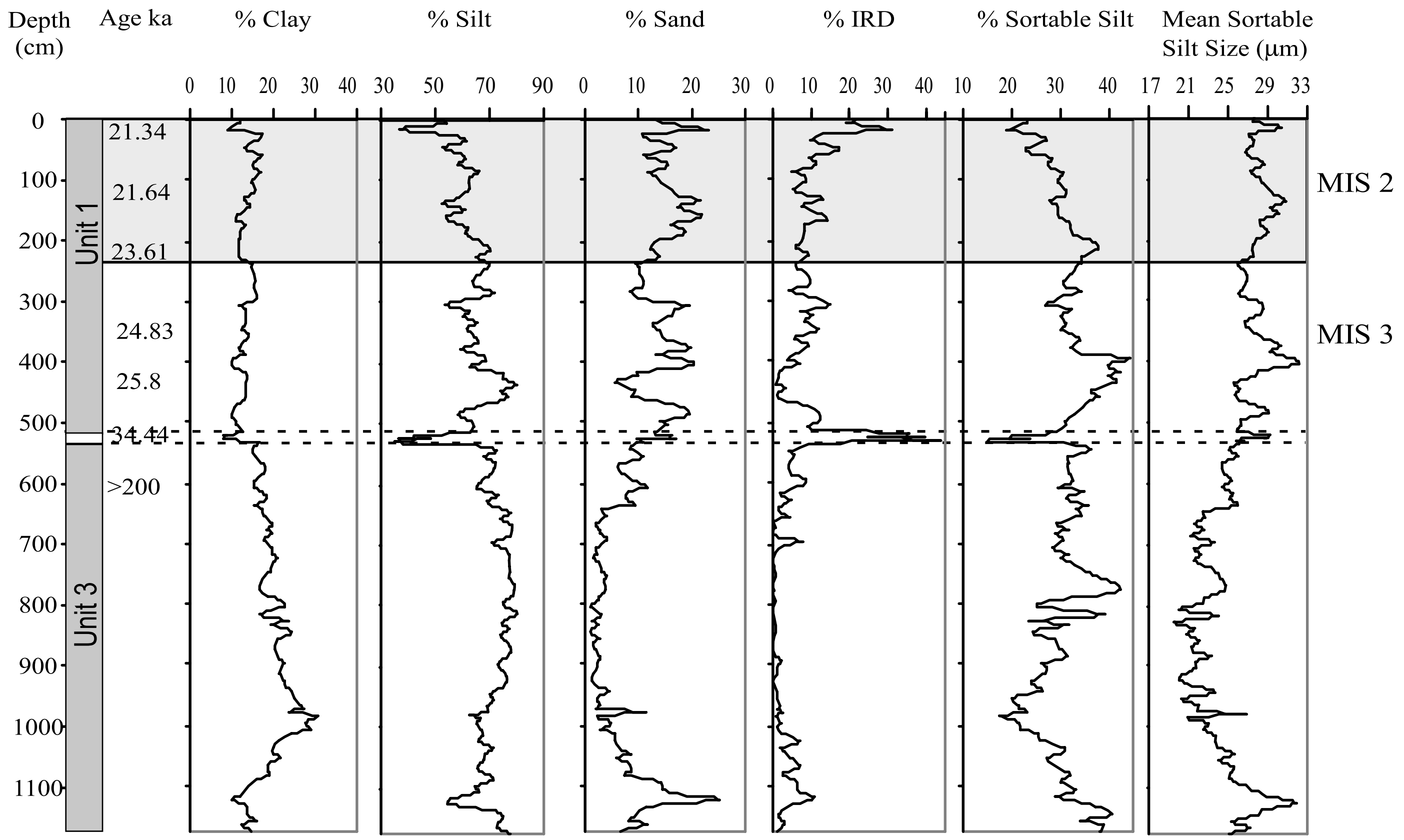

Figure 3.3: Grain size distributions for MD-01-2450 showing volume % of clay fraction (<2 µm), silt (2-63 µm), sand (63-150 µm), IRD (>150 µm), sortable silt (10 - 63 µm) and mean sortable silt size (µm). Marine isotope stages (MIS) and unit boundaries indicated.

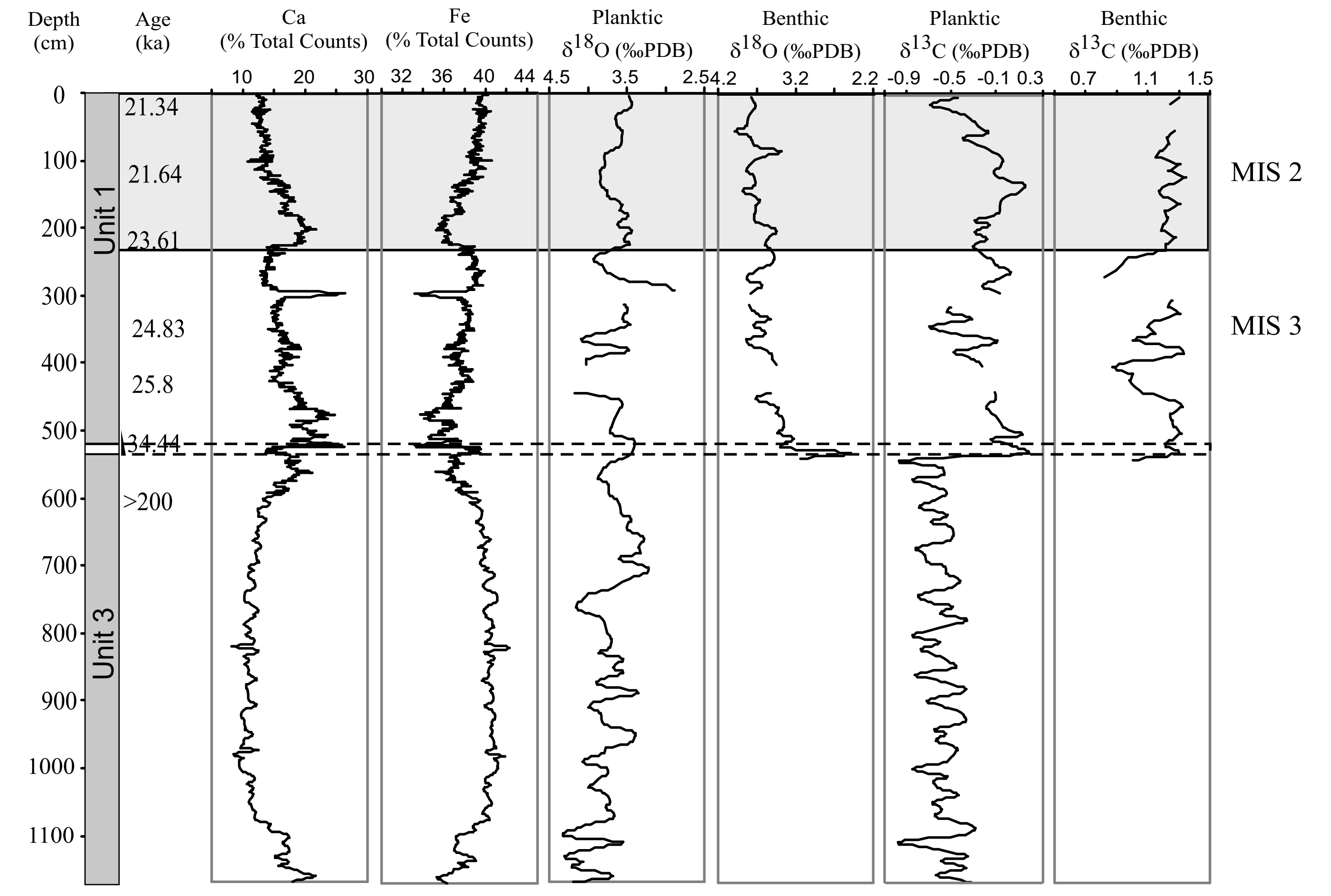

Figure 3.4: Stratigraphy, planktic and benthic $\delta^{18}O$ and $\delta^{13}C$ isotope records and Ca and Fe content (% Total Counts) for core MD-01-2450. Unit boundaries and Marine Isotope Stages (MIS) indicated.

in lithology recovered is suggestive of a range of processes and conditions acting at the time of deposition, Unit 3, the moderately sorted sandy silt can be interpreted as a hemipelagic-glaciomarine drift, with predominantly fine sediment and few incidences of coarser, IRD enriched zones. The small scale lamination indicates that bottom currents were active during deposition. The low abundance of foraminifera in this unit might be explained by low surface productivity often associated during glacials with sea ice coverage (although the IRD input is rather modest) (Maslin et al., 1995; Thomas et al., 1995; Jennings et al., 1996; Chapman et al., 2000; Presti et al., 2003; Spielhagen et al., 2005), or with dilution through a high influx of terrigenous material (Thomas et al., 1995; Robinson et al., 1995) or by dissolution of calcite by corrosive bottom waters.

Unit 2, with its erosive contact to Unit 3 and stacked graded beds is interpreted to be the remains of a debris flow or slump having occurred locally and cutting down into Unit 3. These sediments are similar in composition to that of both the over and underlying units; however the increase in foraminiferal and other biogenic remains indicates that much material had originated from elsewhere, possibly the upper slope. The absence of bioturbation and the thinness of the unit support the interpretation of a sudden event, sorting and mixing sediment from both the immediate sea floor and the shelf.

The sediment of Unit 1 is of both hemipelagic and glaciomarine origin. The grain size distribution and homogenous bioturbated character of the sediment indicates predominantly hemipelagic sedimentation, although with a higher proportion of coarse IRD. The slightly higher mean sortable silt size than in Unit 3 suggests that redistribution of sediments into drifts by stronger bottom currents occurred here. The occurrence of agglutinating foraminifera in Unit 1 may also be an indicator for higher current speeds. Elsewhere, a supply of sediment with which to compose their tests has been identified as a limiting factor for their presence (Thomas et al., 1995). Some of the coarser grain size is attributable to sediment fluxes associated with European Ice Rafting and Heinrich Events 2 and 3 (Snoeckx et al., 1999; Scourse et al., 2000; Auffret et al., 2002). Alternatively, the proximity of ice sheets to the sampling site may influence the grain size of the IRD. Coarser IRD is likely to be entrained and deposited close to ice of a terrestrial or shelfal origin, whereas finer grained IRD is anticipated more distally to the ice front, or below areas covered by sea-ice.

EVENTS AND PROCESSES

Drift

The modern sediments in this area are interpreted to be mounded or confined drifts (McDonnell and Shannon, 2001; De Mol, 2002; Van Rooij et al., 2003), although apart from Van Rooij et al., (in press), their internal structure has not been studied in much detail. Low current speeds are thought to have operated during the deposition of both glaciomarine drift bodies recorded in MD-01-2450. Variability in current intensity may have resulted in the silt-clay laminae seen in Unit 3 and although a slightly higher comparative mean sortable silt size occurs in Unit 1, persistent bioturbation has homogenised the sediment. Low current speeds during glacial periods in the PSB are suggested to be related to a decrease in the influence of MOW, thought to be the driving mechanism behind the bottom currents in this location.

Debris Flow and Slump

Unit 2, the debris flow deposit, contains a high incidence of coarse lithic clasts and biogenic material compared to Units 1 and 3. The event may have been triggered by loading of the upper slope by glaciomarine deposits or by turbidity currents moving sediment off the shelf through cold dense water formation (Bart et al., 1999; Weaver et al., 2000; Dowdeswell et al., 2002). The increase in biogenic content suggests that some shelfal material is included in this unit, or that enhanced productivity was occurring through MIS 3 compared to Unit 3. Interpretations of side scan sonar images in this area by Vermeulen (1996) suggest that periodically active slump folds operate here. Further evidence of debris flows and slumping is provided by Van Rooij et al., (2003).

Microfossil dating of Unit 3 failed to reveal any definitive age beyond >200 ky at 6 m due to a lack of nannofossils. Thus, there has been significant erosion between the two drift units, with at least 170 ky of deposition missing. Using the most conservative of the sedimentation rates calculated for Unit 3, this may equate to approximately 17 m of sediment being removed between Unit 3 and Unit 1, or otherwise a lengthy period of non-deposition.

Bottom current activity

A strong northward bottom current operating in the eastern PSB in the present day has been described by several authors (Pingree and Le Cann, 1989; Rice et al., 1994; Hall and McCave, 1998). Although no direct current measurements exist at the coring site, measurements on this eastern flank of the Porcupine Seabight record a mean flow of 4 cm/s at 1000 m water depth (Pingree and Le Cann, 1989; 1990). Seabed photographs and side scan sonar imagery show variability in present day seafloor morphology (Chachkine and Akhmetzhanov, 1998; Krylov, 1998), and seismic interpretations suggest that drift bodies and sediment waves have been present for a considerable length of time (Wheeler et al., 1998a, McDonnell and Shannon, 2001; De Mol, 2002; Huvenne et al., 2002a; Van Rooij et al., 2003; Van Rooij et al., in press). De Mol et al., (1999) and Beyer et al., (2003) suggest that a contourite current operates in this area between 500 and 1000 m at the present day and indicate this may have been present since the Early Miocene. The origin of the flow is attributed to MOW entering the PSB from the south and circulating in an anticylconic direction (New et al., 2001). Variation of its effects in the PSB through glacial/interglacial cycles has previously been noted by Schoenfeld (2002a), Loewemark et al., (2004) and Dorschel et al., (in press), Dorschel et al., (2005).

Sediment particle size studies of North Atlantic sediments have shown that there is a relationship between mean sortable silt size and bottom current velocity (McCave et al., 1995; Weltje and Prins, 2003). The entire core records a sequence of sediment strongly influenced by fluctuating bottom current intensities. The on average higher mean sortable silt sizes in Units 1 and 2 compared to Unit 3 suggests that less intense currents were operating during the deposition of the older unit.

An increase in sortable silt size towards the Unit 3 and 2 boundary possibly reflects a gradual progression to enhanced bottom water circulation driven by MOW. The coeval increase in % Ca and slight increase in grainsize toward this boundary may be an indication of associated renewed ventilation in the Seabight, with melting icebergs and enhanced down-slope movement of coarser material in Unit 2. The higher Ca values are also caused by the better preserved foraminifera and nannofossils which are in turn indicative of less corrosive bottom waters. Although isotopic values still indicate cold conditions in Unit 1, bottom currents are slightly more intense than in Unit 3 and sediments gradually coarsen as a response to winnowing and from coarse IRD input from drifting ice. The occasionally highly silty laminae in Unit 3 may be an expression of distal deposits of episodic high energy turbidity currents. Rapid and continuous deposition of this type would prevent benthic faunas from settling, thus preserving the laminations.

As for Unit 3, bottom currents operated in glacial periods during the deposition of Unit 1, but were more intense during MIS 3 than MIS 2. The coarser grain size and more frequent bioturbation do not preserve any lamination and the greater preservation of biogenic material indicate that bottom waters were better ventilated than during the deposition of Unit 3. The coarse grain size of the IRD component is likely to be a result of influxes of material from iceberg melting rather than bottom current entrainment.

Hemipelagic deposition

This area of the sea floor appears to have been subject to the slow accumulation of fine-grained sediment in a glaciomarine environment. The effects of glaciation in Unit 3 are interpreted from the lowered current velocities and low foraminiferal abundance related to reduced productivity associated with proximity to ice sheets and dissolution of $CaCO_3$ in a poorly ventilated and cold basin. Unit 1, however, although still dominated by fine sediment contains a significantly larger volume of IRD.

IRD

Based on the grain size distribution of the sediments in Units 1 and 2, and the composition of sediment in Unit 3 with its scarcity of foraminifera and nannofossils, we suggest that most of the coarser grains (>150 µm) in all Units have been sourced from IRD. In Units 1 and 2 this material would have been provided by continuous deposition from sea ice, as well as from fluctuations of both European Ice Rafting

Events 2 and 3 and Heinrich Events 2 and 3 (Snoeckx et al., 1999; Scourse et al., 2000; Auffret et al., 2002). The higher Ca values associated with Unit 1 are related to both the higher incidence of foraminiferal carbonate preserved in this section, with a minor contribution from limestone eroded by the BIIS from the Irish landmass (Scourse et al., 2000; Richter et al., 2001). In Unit 3, fine grained IRD would have entered the study area from ice rafting, meltwater plumes or from turbidity flows transporting ice or glacially derived material from the shelf to the basin floor (Stevens, 1990; Powell, 1990).

CONCLUSIONS

The Late Pleistocene drift sequences preserved in the eastern PSB show that conditions in the PSB have been variable and strongly influenced by glacial events. Variability recorded in chemical properties, sediment composition, grain-size and stable isotope values reflect changes in oceanographic conditions in the PSB as a response to northern hemisphere glaciations during MIS 2 and 3 and earlier, undated events.

Three distinct sedimentary units have been identified. Two glaciomarine drift units are separated by a debris flow, interpreted to have removed at least 17 m of sediment representing a timespan of approximately 160 kyr. Both drift units have formed as a result of the interaction of shelfal material, IRD and bottom currents. The contrasting grain-size between the two units reflects the variable sediment provenance and bottom current regime under which they were deposited. The coarser grained nature of the uppermost drift body is a result of direct ice rafting of material from the European Ice sheets.

Glacial periods are recorded in both units and are interpreted from small transported grain size, a high IRD content in some units, lowered carbonate preservation and low foraminiferal abundance. The lower Ca % of Unit 3 is attributed to poor ventilation of the PSB and higher corrosiveness of bottom waters during its deposition than in Units 1 and 2.

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CHAPTER 4: Modern surface sediment from Propeller Mound, Porcupine Seabight

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ABSTRACT

Sedimentological analyses were conducted on surface sediments collected by box corer from Propeller Mound, a cold-water coral covered carbonate mound in the Hovland Mound Province in the Porcupine Seabight. These samples have been used to determine sedimentological changes around the mound in relation to morphological setting and bottom current regime. Coarse biogenic carbonate prevails on the mound and in knoll-type environments identified on the surrounding seafloor, whereas the

influence of hemipelagic sedimentation increases away from the mound. Winnowed lag deposits of coarse, non-carbonate material were recovered from the seafloor to the west of the mound and on the mound top, suggesting that strong bottom currents have been active here, or that Propeller Mound formed a barrier between turbidites from the shelf and the eastern study region. Current focusing due to topographic relief at the crest of mound is likely to have enhanced the accumulation of coarser grains here.

INTRODUCTION

The Porcupine Seabight (PSB) is characterised by a variety of sedimentary facies. Drift deposits have been identified on its eastern (Van Rooij et al., 2003) and northern margins (Huvenne et al., 2003; Huvenne, 2003), and are thought to be driven by the North Atlantic 'shelf-edge' current and the Mediterranean Outflow Water (White, in press). Carbonate mounds also occur in the PSB (Hovland et al., 1994; Henriet et al., 1998; De Mol et al., 2002; Huvenne et al., 2002). These range in height from less than a meter, to several hundreds of meters in height and support a diverse range of organisms.

Understanding the factors that constrain the livelihood of the carbonate mounds is vital to the preservation of their associated ecosystems which are dominated by cold-water corals. Although considerable work has been published identifying their location, size and range or charaterising surface images from seismic, side scan sonar studies and video footage (Hovland et al., 1994; Wheeler et al., 1998a; Henriet et al., 1998; Huvenne et al., 2002; Van Rooij et al., 2003; Foubert et al., 2005), only little work has been done on sedimentological data from these areas, (Dorschel et al., 2005; Rüggeberg et al., in press; Rüggeberg et al., 2005; Van Rooij et al., in press) . There is evidence of bottom current activity in the vicinity of the mounds, with scoured moats, dropstone pavements and eroded sections documented (Hovland et al., 1994; De Mol et al., 2002; Van Rooij et al., 2003; Dorschel et al., 2005).

An objective of this study is to describe the modern surface sediments and establish if there is variability in grain size distribution in these surface sediments over Propeller Mound in the Hovland Mound Province. We also describe the variability between the carbonate and siliciclastic component of the sediment and relate the grain-size distributions to hydrodynamic conditions at the seafloor.

REGIONAL SETTING

Physiography and hydrography

The Porcupine Seabight off the southwest coast of Ireland is bounded by the Porcupine Bank, the Slyne Ridge, the Irish Shelf and the Goban Spur (Figure 4.1). Its breadth expands from 65 km in the north to 100 km in the south with a coeval increase in water depth from 300 m in the north to more than 2000 m in the south.

The current oceanographic profile is defined by two main water masses. Eastern North Atlantic Water (ENAW) occurs down to approximately 750 m water depth where it is underlain by Mediterranean Outflow Water (MOW), a water mass of higher salinity extending to a water depth of approximately 1000 m (Rice et al., 1991; Van Aken, 2000; White, in press). Bottom currents are active at the seafloor today (Van Rooij et al., 2003) and are driven by the incursion of MOW into the PSB (Mohn, 2000). Along the eastern margin of the PSB, these currents flow from south to north with an average speed of 4 cm/s (Pingree and Le Cann, 1989; Pingree and Le Cann, 1990; Rice et al., 1991). The currents weaken in the north of the Seabight and change direction to the southwest (White, in press). There is evidence of locally higher current speeds throughout the Seabight in the form of coarse surface sediments (Huvenne et al., 2002; Foubert et al., 2005), sediment waves (Akhmetzhanov et al., 2001), channels and drift sediment wedges (Van Rooij et al., 2003). Some of these increases in speed are driven by internal waves and tides (Rice et al., 1991; Mohn et al., 2002; De Mol et al., 2002).

Sedimentation

Present day sedimentation in the PSB is dominated by pelagic to hemi-pelagic sedimentation with low sedimentation rates (Swennen et al., 1998). Reworking of foraminiferal sands by bottom currents has been observed in cores from the northern and eastern margins of the PSB (Rice et al., 1991; Dorschel et al., 2005; Rüggeberg et al., in press) and glacial dropstones and finer grained ice rafted debris (IRD) have been described from several locations at the seafloor (Freiwald et al., 1999; Auffret et al., 2002). There is limited input of terrigenous sediments from the Celtic and Irish shelf areas and the Porcupine Bank today (Rice et al., 1991) and the Gollum Channel system in the southeast of the PSB is not an active conduit for sediments at present (Wheeler et al., 1998b).

Propeller Mound is located in the Hovland Mound Province (HMP), one of three carbonate mound provinces situated in the PSB (De Mol et al., 2002; Huvenne et al., 2003). The mound is characterised by its steep flanks (12° to 60° inclination), tri-lobate shape and features suggesting bottom current activity - namely eroded channels or 'moats' at its base (Freiwald and shipboard party, 2000; Freiwald and shipboard party, 2002; Huvenne et al., 2002; Van Rooij, 2004) dropstone pavements and outcropping hardgrounds (Freiwald and shipboard party, 2002). Living colonies of *Lophelia pertusa, Madrepora oculata* and *Desmophylum cristagalli* have been observed on the mound's uppermost flanks (Freiwald and shipboard party, 2002). The sediment recovered from Propeller Mound is composed mainly of coarse authochtonous carbonate in a sandy-silty matrix (Dorschel et al., 2005; Rüggeberg et al., in press).

DATA AND METHODS

Fourteen box cores from Propeller Mound (on-mound) and from the surrounding sea floor (off-mound) were collected by the German research vessels *R.V. Poseidon* and *R.V. Meteor* (Freiwald and shipboard party, 2000; Freiwald and shipboard party, 2002; Ratmeyer et al., 2004). Their locations are listed in Table 4.1 and surface photographs are shown in Figure 4.2. The cores are classified according to their position on Propeller Mound - 'on-mound' from the mound surface, 'off-mound' from the seafloor adjacent to the mound and 'knoll-type' if the core was retrieved from areas of low topographic relief on the seafloor with a higher relative carbonate content.

The surfaces of the box cores were described on deck directly after recovery. The surface was sampled to a depth of 0.5 cm, providing a bulk sample which was split for

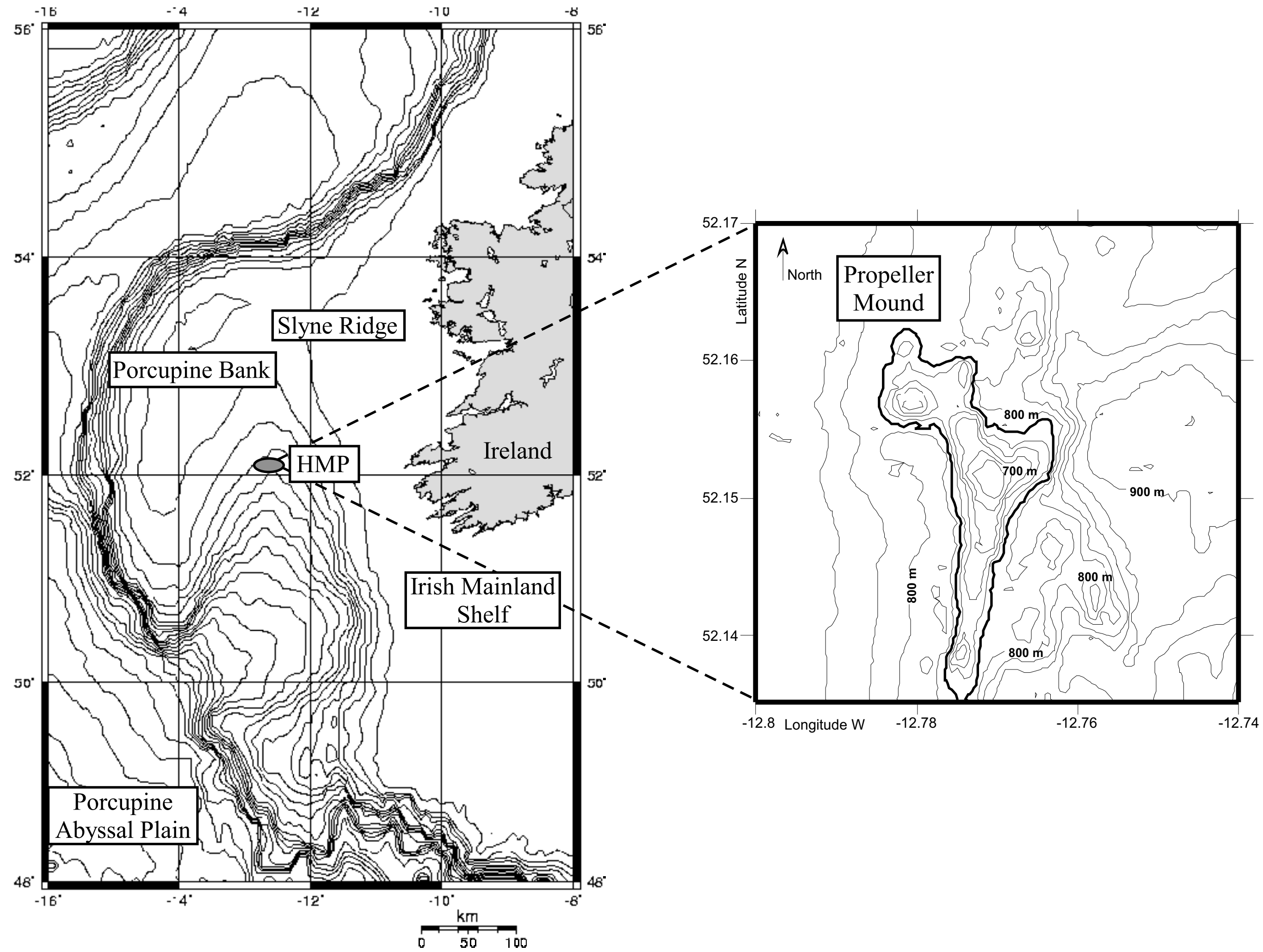

Figure 4.1: Bathymetric map showing the Porcupine Seabight (PSB) southwest of Ireland. Propeller Mound is located in the Hovland Mound Province (HMP) and was mapped during the R/V *Poseidon* cruise POS 265 (Freiwald and Shipboard Party, 2000).

Core No.	Environment	Water Depth	Latitude	Longitude	$CaCO_3$ %	TOC %
GEOB 8059-1	off-mound	804	52 09.20N	12 46.88W	32.7	0.36
GEOB 8073-1	off-mound	761	52 08.75N	12 47.11W	41.2	0.41
GEOB 6718-1	off-mound	890	52 09.58N	12 44.10W	39.4	0.63
GEOB 9245-1	off-mound	769	52 08.84N	12 47.14W	40.7	0.61
GEOB 8074-1	knoll	784	52 08.43N	12 45.88W	46.0	0.63
GEOB 8047-1	knoll	795	52 09.34N	12 46.40W	55.3	0.36
GEOB 8040-1	knoll	809	52 08.52N	12 45.30W	63.6	0.57
GEOB 8039-1	knoll	850	52 08.19N	12 46.09W	47.0	0.47
GEOB 6708-1	on-mound	742	52 09.25N	12 46.19W	38.0	0.49
GEOB 6721-1	on-mound	696	52 09.22N	12 46.31W	44.2	0.43
GEOB 8045-1	on-mound	682	52 09.17N	12 46.13W	69.7	0.40
GEOB 6717-1	on-mound	686	52 09.10N	12 46.23W	77.2	0.43
GEOB 9246-3	on-mound	750	52 08.99N	12 46.20W	46.2	0.40

Table 4.1: $CaCO_3$ % and TOC % for core locations showing geographic position, water depth (m) and mound depositional environment

particle size analysis, grain identification and total organic carbon (TOC) and calcium carbonate measurements (% $CaCO_3$). Identification of grain type was made on sub-samples after sieving over 63 µm mesh. Examination of the grains was performed using a binocular microscope at x10 magnification and visual estimates were made of the percentage contribution of various bioclastic and siliciclastic grains.

To determine total carbon (TC) content, analyses on 25 mg of sub-sample for each location were performed on a Heraeus-CHN-elementary analyser. In subsequent analyses the calcium carbonate was removed by pre-treating the samples with 6 N HCl and drying on a hotplate at 80ºC, thus determining the total organic carbon (TOC) content. The bulk carbonate percentage was then calculated from the TC and the TOC contents using the following equation:

$$CaCO_3\,\% = (TC\,\% - TOC\,\%) \times 8.33$$

Grain size distribution curves for the carbonate and siliciclastic sediment fractions were determined by measurements made using a Coulter LS2000. The bulk surface samples contained excess salt which had to be removed by washing the sediment with water and mechanically agitating it before allowing the samples to settle for several days. This process was repeated until all salt was removed from samples, and resulted in grains being layered according to size fraction. The bulk sediment was then freeze dried and cut vertically to produce a sub-sample containing a representation of the grain sizes present. Two sample sets were prepared in this manner. All sub-samples were sieved to remove grains > 2000 µm and mechanically dispersed with water. One sample set was treated with excess H_2O_2, HCl, and NaOH to remove organic carbon, carbonate and biogenic silica respectively. The second sample set was left untreated. The grain size analyses were run between 3 - 10 times to ensure repeatability. Statistical analysis of the data produced percent volume of the different grain size fractions for carbonate and carbonate free sediment.

RESULTS

Box core surface descriptions

The box core surfaces are predominantly composed of unconsolidated light brown grey to greyish brown and occasionally olive fine sandy silt with clay. An overview of the composition of biogenic clast types in the samples is given in Table 4.2. Among the non-bioclastic grains quartz is the dominant component in all locations.

On-mound

On-mound surfaces typically contain coral material (dominated by *L. pertusa*, *M. oculata* and *Desmophyllum sp.*) ranging in size from several millimetres up to 20 cm. These are either partially buried by the surrounding hemipelagic sediment or are fully exposed on the surface. Dead coral fragments are heavily bored, and are white to grey in colour, or have heavily oxidised surfaces and are colonised by a variety of organisms whose remains compose various proportions of the sediment (Table 4.2). The distribution of these macrofaunal remains on Propeller Mound is patchy, with areas of living coral and zones of hemipelagic sediment cover with no large faunal remains. Coral bearing zones proliferate on the top of the mound and the western flanks. Where large bioclastic remains are rare, the surface sediments are composed of sandy silt or sandy silty clay containing planktic foraminifera, pteropods and siliciclastic material. This hemipelagic ooze occurs in the North between the NE and NW spurs of Propeller Mound, and also forms the matrix material burying large bioclasts and lithoclasts. Bioturbation is evident in the ooze sediment, with burrows ranging from <1 – 10 mm in diameter. Large lithoclasts up to 20 cm in length occur on-mound and in box core surfaces at the base of the mound and are highly angular or well rounded (e.g. GEOB 8039-1, Figure 4.2).

Off-Mound

In off-mound environments the box core surfaces contain very few large bioclastic remains (Table 4.2, Figure 4.2). In general, the sediment surface is an unconsolidated sandy silty clay containing abundant planktic foraminifera, pteropods and siliciclastic material with rare benthic foraminifera and echinoid or bivalve remains. Non -

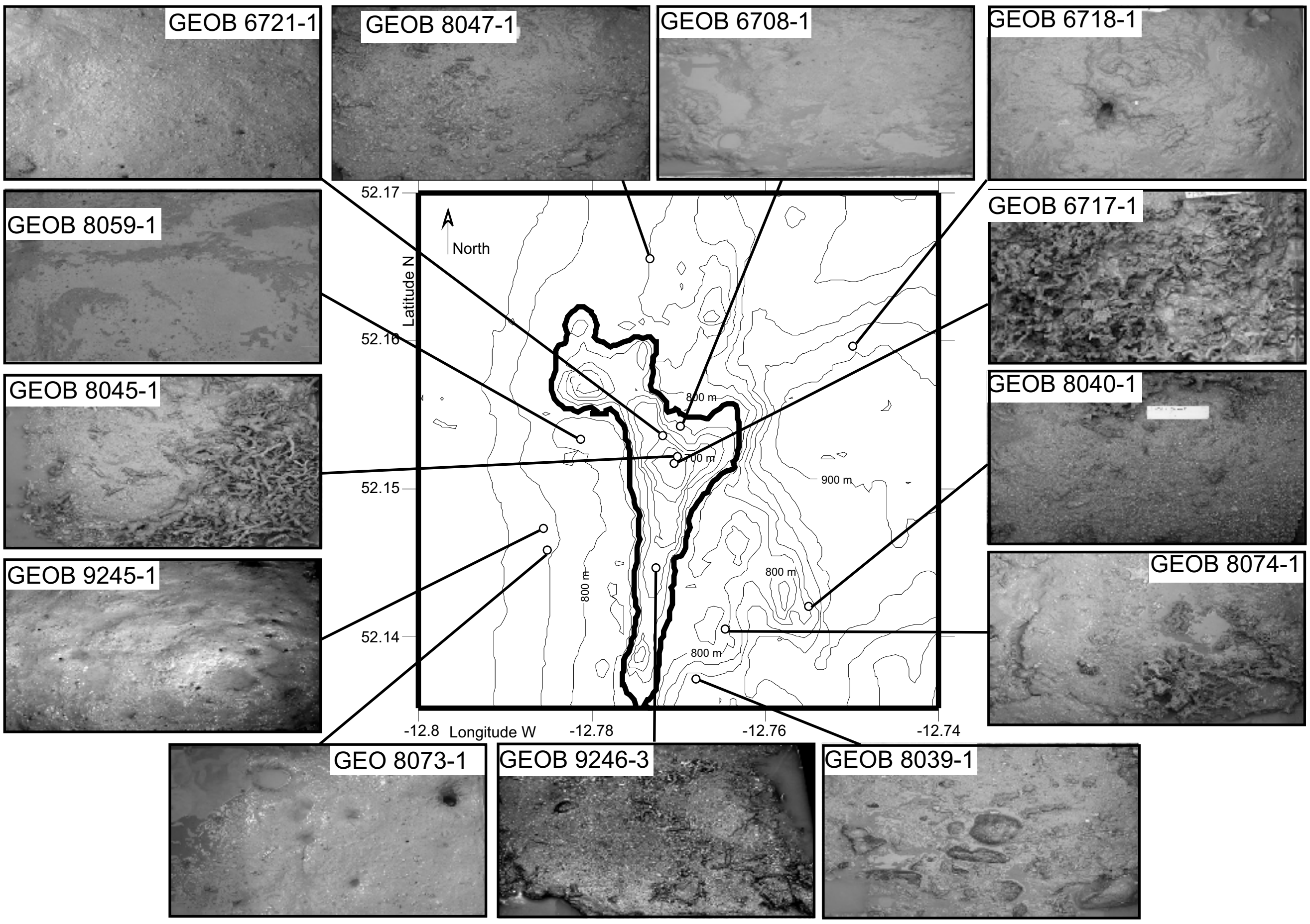

Figure 4.2: Location of box cores over Propeller Mound and photographs of recovered sediment surfaces. The 780 m water depth contour is indicated in bold to emphasise the outline of Propeller Mound.

Components (% of Bulk Sediment)

Sample ID	Environment	Coral	Foraminifera		Mollusc	Echinoderm	Undifferentiated	Lithic
			Planktic	Benthic				
GEOB 8059-1	off-mound	0	60	3	0.1	0.1	6.8	30
GEOB 8073-1	off-mound	0	80	7	0	0.1	2.9	10
GEOB 6718-1	off-mound	0	90	2	2	0.1	3.9	2
GEOB 9245-1	off-mound	0	90	2	0	0	0	8
GEOB 8074-1	knoll	35	45	5	2	3	5	5
GEOB 8047-1	knoll	15	60	3	3	2	5	12
GEOB 8040-1	knoll	20	30	10	20	5	10	5
GEOB 8039-1	knoll	30	40	5	10	5	0	10
GEOB 6708-1	on-mound	5	60	2	5	2	1	25
GEOB 6721-1	on-mound	35	45	5	2	2	1	10
GEOB 8045-1	on-mound	45	25	5	10	2	3	10
GEOB 6717-1	on-mound	45	30	5	7	5	3	5
GEOB 9246-3	on-mound	30	20	7	10	2	4	20

Table 4.2: Bulk analysis of sediment >63μm to show percentage contribution of various skeletal components. Undifferentiated skeletal components comprise crustaceans, chitons, brachiopods, bryozoa, otholiths and sponge spicules

calcified worm tubes up to 15 cm in length and foraminifera on elevated stalks above the soft surface were recovered in some locations (Freiwald and shipboard party, 2000). The surfaces of these box cores are highly bioturbated, with burrow diameters ranging from < 1 – 30 mm in diameter. Coarser lithoclastic material also occurs in some locations with fragments ranging in size up to > 20 cm. Several of the locations recovered unexpectedly large amounts of coral rubble (north and southeast), in similar volumes to that seen in on-mound locations, with a comparable related bioclastic assemblage. We have termed these 'knoll type' locations.

$CaCO_3$ and TOC contents

Analytical results for the $CaCO_3$ and TOC contents are shown in Table 4.1. Calcium carbonate values fluctuate from 32.7 % to 77.2 % (average 47.6 %). Off-mound locations display lowest $CaCO_3$ values, averaging 39 %. Higher values occur on-mound, averaging 50 %, with a peak of 77.2 % at site GEOB 6717-1. The knoll-type locations also record high values with an average of 55 %, considerably higher than that measured in typical off-mound locations. All these values are within the range of those obtained for down-core measurements from long sediment cores collected at and around Propeller Mound (Dorschel et al., in press; Rüggeberg et al., in press).

TOC measurements over the area are generally low, ranging from 0.35 % at GEOB 8047-1 to 0.63 % at GEOB 8074-1 to the southeast of Propeller Mound. Generally, values tend to be higher in off-mound areas. These off-mound locations average 0.53 % TOC, and are similar for knoll-type locations, with an average of 0.52 %. The on-mound average is lower at 0.43 %.

Grain Size Distribution

Grain size distributions of the surface sediments show variation linked to the morphological setting of the sample location (Figure 4.3). Mean grain sizes for all environments and size categories are summarised in Table 4.3. Comparisons of the grain size distributions for bulk and decalcified samples indicate that carbonate and siliciclastic material are not evenly distributed in all the size classes.

Bulk Sediment analyses

Coarsest sediments occur in on-mound and knoll-type locations. These sediments are silty sands with a mean modal size in the sand fraction (~315 µm) and a second mode in the silt fraction (~17 µm). A similar trend can also be seen in the off-mound sediment to the west of Propeller Mound where the bimodal distribution has corresponding modes at 157 and 28 µm. Finest sediments occur in the deeper waters to the east of the mound

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Carbonate Sediments

The carbonate fraction in all environments is bimodal. Carbonate dominates the coarse (sand) fraction in on-mound and knoll locations, with the mound top and western margins composed of the coarsest carbonate material.

In off-mound samples the carbonate sand content is lower. The distribution is common for hemipelagic sediments dominated by fine and sortable silts with foraminiferal sand and clay. Exceptions occur at GEOB 9245-1 and GEOB 8073-1 where sediment is dominated by sand.

Siliciclastic Sediments

As for the carbonate fraction, the siliciclastic sediments also show variability in their size distribution. There are two distinct sandy zones. One is well defined as the top of Propeller Mound, where a peak in the sand fraction occurs at > 105 µm, and the other is situated on the seafloor to its west, with a peak in the same size range. A decrease in volume % occurs in all samples between the grain size range of 66 and 105 µm.

In the on-mound and knoll-type samples the mean siliciclastic grain size is considerably lower than that of the carbonate fraction (with the exception of GEOB 6721-1). Again, there is an apparent bimodal distribution, particularly in the locations on the western tops and flanks of the mound. Lowest sand volume and lowest mean grain size occur to the east of the mound crest and in eastern off-mound locations. Knoll-type locations are dominated by sortable silt. Large lithic fragments interpreted

SILICICLASTIC GRAINS

Core No.	Volume			Sortable Silt			Mean Grain Size
	Clay	Fine Silt	Sand	Volume	Mean	Mode	
GEOB 8059-1	4.83	9.19	35.21	18.09	28.98	28.70	158.09
GEOB 8073-1	6.64	13.44	16.47	22.22	29.70	31.51	81.56
GEOB 6718-1	7.03	14.49	6.26	32.87	31.23	37.97	28.43
GEOB 9245-1	4.30	8.38	26.89	19.69	30.86	43.72	107.26
GEOB 8074-1	9.20	19.28	3.28	22.22	25.37	11.84	19.14
GEOB 8047-1	6.94	12.06	7.62	18.09	27.61	28.70	58.14
GEOB 8040-1	5.29	10.85	1.17	19.09	25.81	26.14	17.74
GEOB 6708-1	6.52	13.49	17.57	24.41	28.38	26.14	71.15
GEOB 6721-1	2.37	4.79	38.88	9.77	30.12	38.08	266.03
GEOB 8045-1	4.17	9.89	1.67	14.53	22.80	13.61	21.30
GEOB 6717-1	2.56	6.48	0.40	13.33	26.96	16.40	18.72
GEOB 9246-3	3.90	10.26	19.56	20.06	26.85	23.81	111.67
GEOB 8039-1	6.71	14.84	6.81	24.61	27.92	28.70	40.26

CARBONATE GRAINS

Core No.	Volume			Sortable Silt			Mean Grain Size
	Clay	Fine Silt	Sand	Volume	Mean	Mode	
GEOB 8059-1	1.73	9.41	9.41	12.17	33.70	60.52	34.96
GEOB 8073-1	1.93	10.14	22.01	7.08	33.27	60.52	83.69
GEOB 6718-1	4.87	19.45	9.92	5.11	11.59	10.29	41.95
GEOB 9245-1	3.58	12.60	14.57	9.96	29.56	10.29	46.35
GEOB 8074-1	1.90	8.92	20.52	14.68	10.29	34.59	118.64
GEOB 8047-1	n/a	2.78	58.59	0.03	10.29	10.29	483.56
GEOB 8040-1	2.22	8.16	49.50	3.77	40.60	55.13	477.95
GEOB 6708-1	1.24	7.90	22.25	6.65	31.99	10.29	175.12
GEOB 6721-1	4.04	13.22	13.78	13.13	26.50	10.29	165.80
GEOB 8045-1	2.86	5.57	60.89	3.32	33.13	60.52	217.79
GEOB 6717-1	3.76	10.78	60.92	1.77	30.07	10.29	395.13
GEOB 9246-3	1.16	2.63	49.43	n/a	n/a	n/a	372.18
GEOB 8039-1	1.48	5.64	40.35	0.82	42.12	60.52	266.38

Table 4.3: Grain size parameters for siliciclastic and carbonate sediment showing volume % clay, fine silt, sand and sortable silt, as well as mean and modal sortable silt sizes. Mean grain sizes also shown.

to be dropstones from the last glacial can be seen in photographs from the mound surface and from the base of the southeastern mound flank.

DISCUSSION

Recent sedimentation in the Porcupine Seabight is controlled by the interaction between bottom water circulation, sediment supply and autochthonus carbonate production. Sediment sampling and ROV and side scan sonar images in the Hovland Mound Province indicate that this is an area of ‘living’ coral mounds with active bottom current flow (Freiwald and shipboard party, 2000; Freiwald and shipboard party, 2002; Huvenne et al., 2002a, Rüggeberg et al., 2005). In addition, formerly active sedimentary processes, such as the input of ice-rafted material during the last glacial, still leave a visible impact on the surface sediments. For Propeller Mound these processes have resulted in three sedimentary zones that can be distinguished on the basis of grain size analysis, calcium carbonate and organic carbon content variability and surface sediment texture: on-mound, off-mound and knoll-type (Figure 4.4).

The on-mound and knoll-type regions are characterised by on average higher $CaCO_3$ contents and a greater carbonate grain size reflecting the higher incidence of coarse bioclastic remains than in the off-mound locations. The siliciclastic sediments at and around Propeller Mound are of both hemipelagic and glaciomarine origin, with variations in sediment coarseness apparently dependant on the location of the sampling site.

Sediment supply to Propeller Mound

I. Carbonate sediment supply

The composition of the carbonate sediments varies significantly across the study area, with the majority of the $CaCO_3$ occurring in the sand fraction. In off-mound locations this is dominated by planktic foraminifera, and in on-mound and knoll environments it is from autochtonous production by either prolific coral growth or the large diversity of carbonate producing organisms associated with the coral ecosystem.

Local variability in coarse bioclastic distributions is expected due to the slumping of fossil material, exposure through erosion and from environmental constraints determining optimal growth positions for the fauna.

In all Propeller Mound environments, the components < 63 µm are likely to be hemipelagic in origin, and composed of coccoliths and fragmented foraminifera, as is also common for other hemipelagic sediments (McCave et al., 1995). Additionally, in on-mound and knoll-type environments a considerable amount of this fraction originates from bioerosion, micritisation, degradation of macrozoobenthic remains, chemical and microbiological precipitation (Monty, 1995; Beuck and Freiwald, 2005). The relative amount of planktic foraminifera is lower in on-mound locations compared to off-mound sites. This is partially a dilution factor due to the occurrence of other biogenic material. The amount and diversity of benthic foraminifera is higher on-mound, and a description of the benthic foraminiferal assemblage is given by Rüggeberg et al., (submitted).

II. Siliciclastic sediment supply

Modern sediment supply to the PSB is mainly by hemipelagic sedimentation of suspended matter and by settling from intermediate and benthic nepheloid layers, which has been noted to occur in other locations in the PSB (Rice et al., 1990; Vermeulen, 1996). As bottom currents are generally not strong enough to transport grains greater than 63 µm (McCave, 1984), the large lithic clasts (e.g. at GEOB 8039-1) and coarser sands must have been emplaced by other means: either by glacial events or by turbidity currents. The large clasts found on top of Propeller Mound are obviously not transported by turbidity currents and, thus, must be deposited as ice-rafted detritus during glacial periods.

III. Sediment texture and transport

The two sets of grain size analyses allow us to determine if different current regimes have operated over Propeller Mound in its recent history and if these effects have resulted in a different record in the carbonate and non-carbonate sediments. From the grain-size distribution curves (Figure 4.3) it is possible to determine whether the bottom sediment deposits were formed by erosional or depositional processes.

i) Carbonate Sediment

As shown above, coarsest carbonate material occurs in on-mound and knoll environments as a direct reflection of the autochtonous production by biota in these locations. Additionally, we suggest that coarse carbonate material reaches the lower slopes and seafloor adjacent to Propeller Mound by slumping and debris flows (Dorschel et al., 2005). The lower slope gradient on the eastern flank of Propeller Mound may be a result of such down-slope sediment movement, with limited current activity moving it away, or stronger currents in the west incising a deeper moat at the base of the mound.

Allochtonous sediment preserved on Propeller Mound and the seafloor around it reveal more about the current intensities operating here. In all locations there is evidence of retention of hemipelagic carbonate grains, although on the seafloor to the east and between the northern 'spurs' of Propeller Mound, a broader range of 'transportable' carbonate material is retained. It is possible that lower current intensities in these locations have not winnowed the fine fraction away. Dilution effects of siliciclastic material and coarser particles enhance an apparent lower occurrence of these fine carbonate grains to the west and at the crestal areas of Propeller Mound.

ii) Siliciclastic Sediment

It is more likely that the siliciclastic component can serve as a better indicator for hydrodynamic activity than the carbonate sediment. Grains greater than 63 µm in size are often interpreted as ice rafted detritus on the Atlantic Margin (Manighetti and McCave, 1995b; Hall and McCave, 1998) and at Propeller Mound today are likely to be transported by debris flows and turbidity currents to its lower flanks, or were emplaced during glaciations. As in the carbonate fraction, transportable grains are retained in all locations indicating that present day conditions are accumulative rather than erosive. This has also been suggested from bedforms seen in sidescan sonar (Huvenne et al., 2002a) and seismic studies (De Mol et al., 2002). Although there is only a small range in variability in the average sortable silt size for the different locations, the mean size tends to be highest on the western side of Propeller Mound, indicating that current speeds may be slightly higher in this region. However, the pattern of sediment textural variations for the fraction greater than 63 μm across the study area is one of a sand enriched zone on the western off-mound and crestal on-mound locations. This suggests that different processes have affected the eastern and western sides of the mound.

Are bottom currents acting at Propeller Mound?

Apart from direct measurements, indicators of bottom currents may be discerned from seafloor structures or from the grain size distributions. Current activity in a marine setting has been described by mean grain size of sediments at a particular location (McCave et al., 1995). The sortable silt fraction between 10 – 63 μm is interpreted to be the most useful parameter in palaeocurrent speed determination as the grains behave in a non-cohesive manner. This proxy has been applied in several other studies in the North Atlantic (Yokokawa and Franz, 2002; Baas, 1997; Austin and Evans, 2000). For the siliciclastic fraction, the volume of sediment in this size range is between 9 and 32 %. Bottom currents transporting fine sand/silt are interpreted as having velocities peaking at 25-30 cm/s (Masson et al., 2002), within the range of those previously measured in the Hovland Mound Province (Freiwald and shipboard party, 2000).

The morphology of the seafloor adjacent to Propeller Mound provides evidence for bottom current activity. A moat on the western flank of Propeller Mound has been interpreted to be an erosive feature (Freiwald and shipboard party, 2000; Freiwald and shipboard party, 2002; Huvenne et al., 2003; Van Rooij et al., 2003). A NW – SE trending drift sediment wedge is interpreted from the bathymetric profile to the west of Propeller Mound by Freiwald and shipboard party, (2002). Outcropping hardgrounds (Dorschel et al., 2005) and the occurrence of a dropstone pavement (Freiwald and shipboard party, 2002) may indicate that winnowing and removal of significant volumes of sediment have occurred here.

Highest concentrations of the living corals *Lophelia pertusa, Madrepora oculata*, and *Desmophyllum cristagalli* are found along the exposed southerly plateau of Propeller Mound (Freiwald and shipboard party, 2000). Their occurrence is thought to be constrained by hydrodynamics, food supply and the presence of a hard substrate for

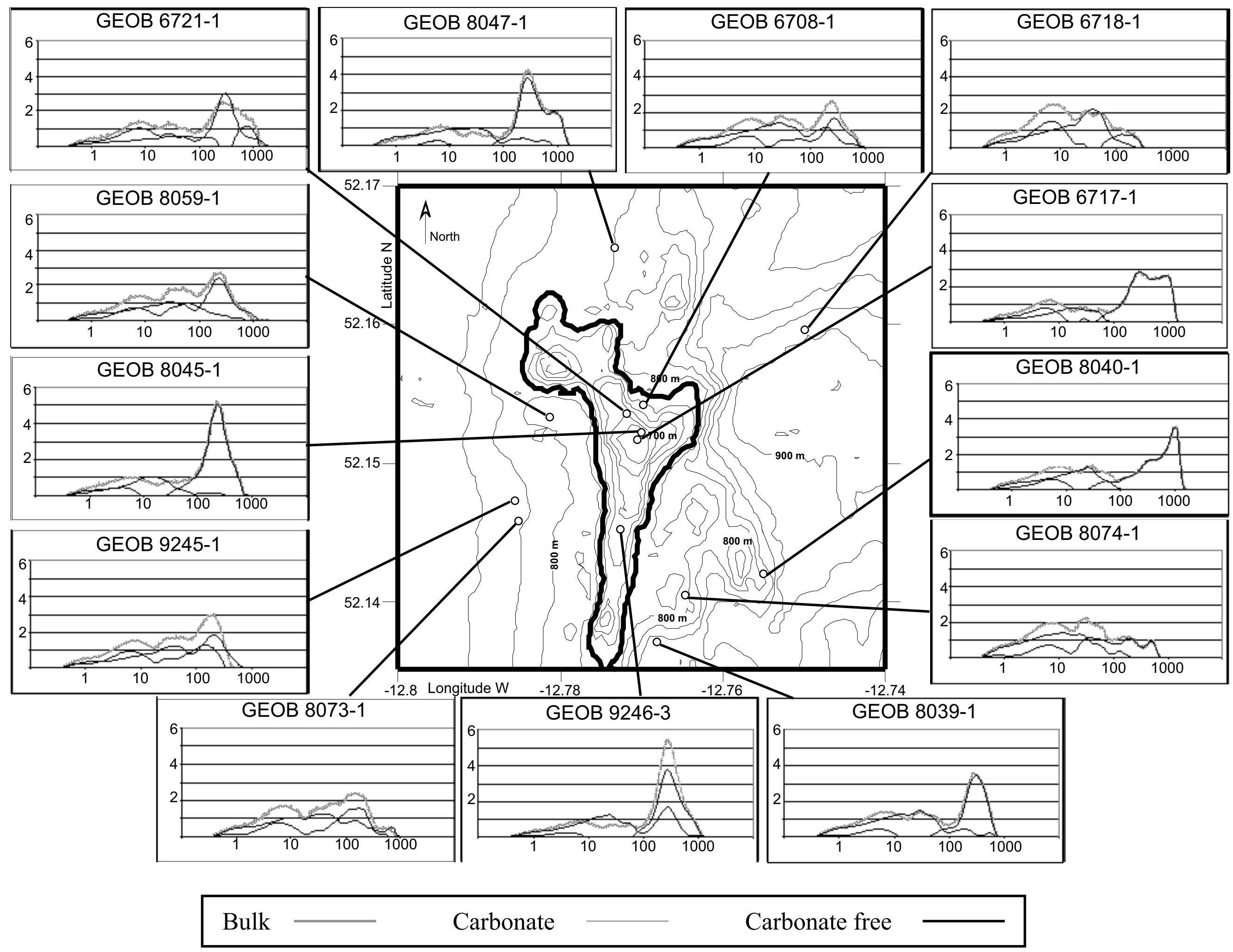

Figure 4.3: Grain size distribution measured on a Coulter LS 2000 for bulk, decarbonated and carbonate surface samples for box core surface sediment samples over Propeller Mound. X-axis: grainsize (μm), Y-axis: % Volume of total analysed sediment volume. The 780 m water depth contour has been bolded to show the outline of Propeller Mound.

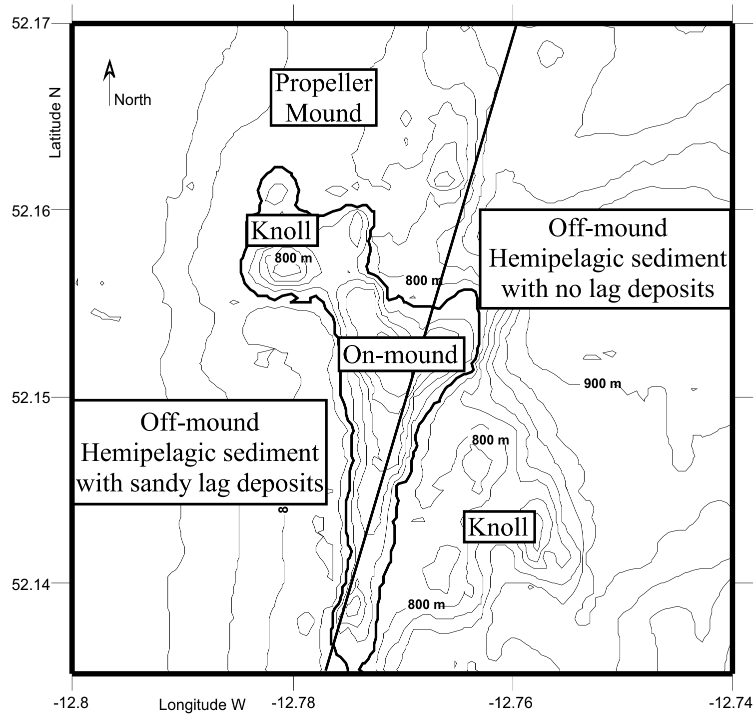

Figure 4.4: Sedimentary zonation over Propeller Mound showing on-mound and knoll bioclastic carbonate dominated areas and off-mound region. Line separates hemipelagic sediment on the seafloor to the east from coarser sediments on the western mound area and seafloor.

colonisation (Freiwald and Wilson, 1998; Freiwald et al., 1999). An association between high current velocities and coral mounds has been noted in many studies from the PSB (Freiwald and Wilson, 1998; Freiwald et al., 1999; De Mol, 2002; Van Rooij et al., 2003; Dorschel et al., 2005). Living coral on the tops of the mounds in the PSB today suggests that currents are still active, providing requisite conditions for coral growth, and ensuring that polyps are not buried by sediment. Steep slopes (here, the flanks of Propeller Mound) may enhance current velocities (Faugeres et al., 1993; Faugeres et al., 1998; Trasvina-Castro et al., 2003; Turnewitsch et al., 2004) and this may also explain why there is an increase in sand content on top of the mound.

The grain size distributions displayed by the non-carbonate fraction show peaks in coarse material to the west of and on Propeller Mound. These may be 'lag' deposits of ice rafted debris winnowed by stronger currents in the past (McCave et al., 1995; Manighetti and McCave, 1995a), now mixed with hemipelagic and finer grains by bioturbation and moderate current activity. The absence of these peaks in the eastern region of the study area could be a reflection of lower currents speeds in the past compared to the west, or even lower current speeds at the present day, with retention of hemipelagic sediment covering evidence of past winnowing. If this was the case, Propeller Mound itself must form a barrier to bottom current flow. Local hydrodynamics are expected to play a role in current forcing at Propeller Mound. The shape of the seafloor in the HMP is also likely to direct bottom currents in a different orientation to those measured in the south eastern PSB. Elsewhere in the PSB, variability in bottom current speeds and directions have been attributed to seasonal and tidal influences (Rice et al., 1994; White, 2003; White, in press) and it is probable that this may occur within the study region too.

Turbidite and debris flows

The movement of coarse sediment from the shelf to the seafloor in the PSB throughout its history has been discussed by several workers (e.g. Knutz et al., 2001; Auffret et al., 2002), and the direction of flow movement proposed by Rüggeberg et al., (2005) could provide another explanation for the coarser sediment to the west of Propeller Mound. Material moved off the shelf during sea level lowstands would have been prevented from reaching the eastern side of Propeller Mound by the mound itself. Many hiatuses have been recorded from on-mound cores (Dorschel et al., 2005), and these may have had the capacity to enrich coarser material near the mound base, as e.g. in the moat at its western flank or in the southeast. Winnowing since these events has resulted in the multimodal distribution displayed by the non-carbonate sediments with peaks in the sand fraction.

CONCLUSIONS

The distribution of sediments recovered from Propeller Mound and the surrounding seafloor is the result of an interaction between bottom currents of varying speeds, mound growth and sediment input. The present sea level high-stand is characterised by a low terrigenous sediment supply to the PSB and redistribution of sediments by bottom currents.

Three distinct sedimentary environments have been identified in the Propeller Mound region: on-mound, off-mound and knoll-type. All these display a strong hemipelagic signal, and a high siliciclastic component. On-mound and knoll type environments have high $CaCO_3$ contents and coarser grain sizes compared to off-mound environments, mainly as a result of their high biodiversity. It is likely that knoll-type locations have formed by slumping of material from on-mound locations which has subsequently been recolonised by corals, or may represent smaller mounds growing adjacent to Propeller Mound.

Lag deposits of siliciclastic sediment occur on the seafloor to the west of Propeller Mound and at the mound crest. This distribution may be attributed to winnowing by bottom currents concentrating sand grains, or by turbidite emplacement of coarse shelfal material from the Porcupine Bank on the seafloor to the west of the mound. A reason for the lack of the lag deposits in the eastern study area is speculative; Propeller Mound could act as a barrier to the flow of either turbiditic material or bottom currents from the west, or the effects of topographic forcing of currents may be greatly reduced in locations to the east of the mound because of their greater distance from it. Coarse sediment lags on the crest of the mound are likely to be the result of current focussing due to topographic relief.

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CHAPTER 5: Variation in Carbonate Mound Sediments: Significance for the Pleistocene Development of Propeller Mound, Porcupine Seabight

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ABSTRACT

Variations in the lithology and faunal assemblages in cores from Propeller Mound in the Hovland Mound province of the northern Porcupine Seabight (NE-Atlantic) are used to characterise the Pleistocene development of a carbonate mound. Based on lithologic, isotopic and grain size data the core could be divided into four sedimentary facies types, which reflect different hydrodynamic settings. During glacial periods, the reduced influence of Mediterranean Outflow Water led to decreased bottom current speeds and less favourable conditions for coral growth. The re-establishment of more vigorous interglacial current conditions often resulted in hiatuses followed by periods of coral growth. However, most effective mound growth was restricted to interstadials when bottom current strength allowed both coral growth and the deposition of pelagic sediments. Interestingly, the recovered sediment column of 13.8 m with a basal age of ~1.5 Ma accounts for an estimated 30% of the whole mound history, although it represents only ~5% of the mound thickness. Thus, in the earlier part of the development of Propeller Mound, mound growth must have been much faster.

INTRODUCTION

Carbonate mounds are known throughout geological history and there are examples from many different environments. Modern carbonate mound systems occur in several locations in the North Atlantic Ocean, although those in the Porcupine Seabight (PSB) off the coast of south western Ireland have been the most intensely studied in recent years. Here, the mounds occur in three provinces: the Belgica, Hovland and Magellan Mound Provinces, distinguishable from one another by variation in mound morphology and geographic location. The carbonate mounds in the PSB range in height from <1 m to 200 m, and are either solitary conical structures, or complex composite mounds. A significant portion of the mounds is buried by seafloor sediment (De Mol et al., 2002; Van Rooij et al., 2003). It is thought that these mounds share a common initiation period during the Early Pliocene (De Mol, 2002).

The majority of the published work on these systems to date has been seismic or side-scan sonar based, or has dealt with surface sediment or mound ecology (e.g. Hovland et al., 1994; De Mol et al., 2002; Huvenne et al., 2002; Henriet et al., 2002; Huvenne et al., 2003; Huvenne, 2003; Rüggeberg et al., submitted; Foubert et al., 2005). Although models for mound growth exist (Hovland and Thomsen, 1997; Henriet et al., 1998; Henriet et al., 2002) and cyclical development related to coral growth and hydrodynamics has been postulated (De Mol, 2002), this has only been applied directly to observations of sediments recovered from short (< 6 m) cores from the carbonate mounds (Dorschel et al., in press; Dorschel et al., 2005; Rüggeberg et al., in press). This study presents a view into the internal structure of one mound in the HMP using longer a longer core (13.8 m) with the aim of reconstructing some of the processes driving its formation and establishing a relationship between the sedimentary units preserved and the hydrodynamics prevailing in the PSB during its growth.

REGIONAL SETTING

Physiography and oceanographic regime

Propeller Mound is located in the Hovland Mound Province (HMP), one of three carbonate mound locations in the PSB off the south west coast of Ireland (Figure 5.1). The PSB is bounded to the north by the Slyne Ridge, to the west by the Porcupine Ridge, to the east by the Irish Mainland Shelf that merges to the southeast with the Goban Spur. The Seabight is 150 km long with a N-S orientation, widening from 65 km in the north to 100 km in south. The PSB also deepens southwards, from 300 m in the north to more than 2000 m in the south. Water depths in the HMP range from 653 m at the summit of Propeller Mound to 920 m. This depth range places the HMP within the zone of influence of two water masses, Eastern North Atlantic Water (ENAW) which occurs down to approximately 750 m water depth and Mediterranean Outflow Water occurring down to 1000 m (Rice et al., 1991; Van Aken, 2000; White, in press). The MOW is warmer and more saline than the ENAW and is thought to drive bottom currents in the PSB at depths between 600 and 1000 m, with a reduction (or absence) of flow during glacial periods (Schoenfeld and Zahn, 2000).

Bottom currents in the south eastern PSB flow in a northerly direction with an average velocity of 4 cm/s at 1000 m (Pingree and Le Cann, 1989; Pingree and Le Cann, 1990; Rice et al., 1991). Calculations of current speeds from observed bedforms suggests that speeds may occasionally be higher (Akhmetzhanov et al., 2001), possibly enhanced locally by internal waves and tides (Rice et al., 1991; Mohn et al., 2002; De Mol et al., 2002).

Sedimentation

Pelagic to hemipelagic sediments dominate the carbonate mound regions of the PSB today, with low sedimentation rates (Swennen et al., 1998; Freiwald and Party, 2002). Although modern terrigenous input is low (Tate, 1993), some material is supplied from the Celtic and Irish shelves, with limited sediment provided by the Porcupine Bank (Rice et al., 1991). Ice rafted debris (IRD), a relict of the Atlantic Margin's Pleistocene glacial history is mixed with these sediments and has been observed in several locations in the Porcupine Seabight (Freiwald et al., 1999; Auffret et al., 2002). Since these times, bottom currents have redistributed and winnowed these sediments (Rice et al., 1991; Dorschel et al., 2005; Rüggeberg et al., in press).

Analyses of seismic profiles have shown that Propeller Mound is the largest mound in the HMP today, being approximately 280 m high from crest to base with steep flanks, ranging from about 12° to 60° in inclination (De Mol et al., 2002). It is a 'composite' mound developed by the amalgamation of several smaller mounds and drift sediments. The sediment contains mostly > 50% $CaCO_3$ mainly sourced from the remains of organisms observed on the mound (Dorschel et al., in press; Rüggeberg et al., 2005), and typical of other modern carbonate mounds in the northeast Atlantic (Swennen et al., 1998; Sumida and Kennedy, 1998; Saoutkine, 1998; De Mol et al., 1998; Mazurenko, 1998; Wilson and Herbon, 1998; Akhmetzanov et al., 1998; De Mol et al., 1999; Mazurenko, 2000; De Mol et al., 2002; Rüggeberg et al., 2005; Dorschel et al., 2005). The mound sediments are typically heavily bioturbated and contain evidence of numerous unconformities or hiatuses through a strongly fragmented stable isotope and stratigraphic record (Dorschel et al., 2005; Rüggeberg et al., in press). The removal of the sedimentary record from Propeller Mound has

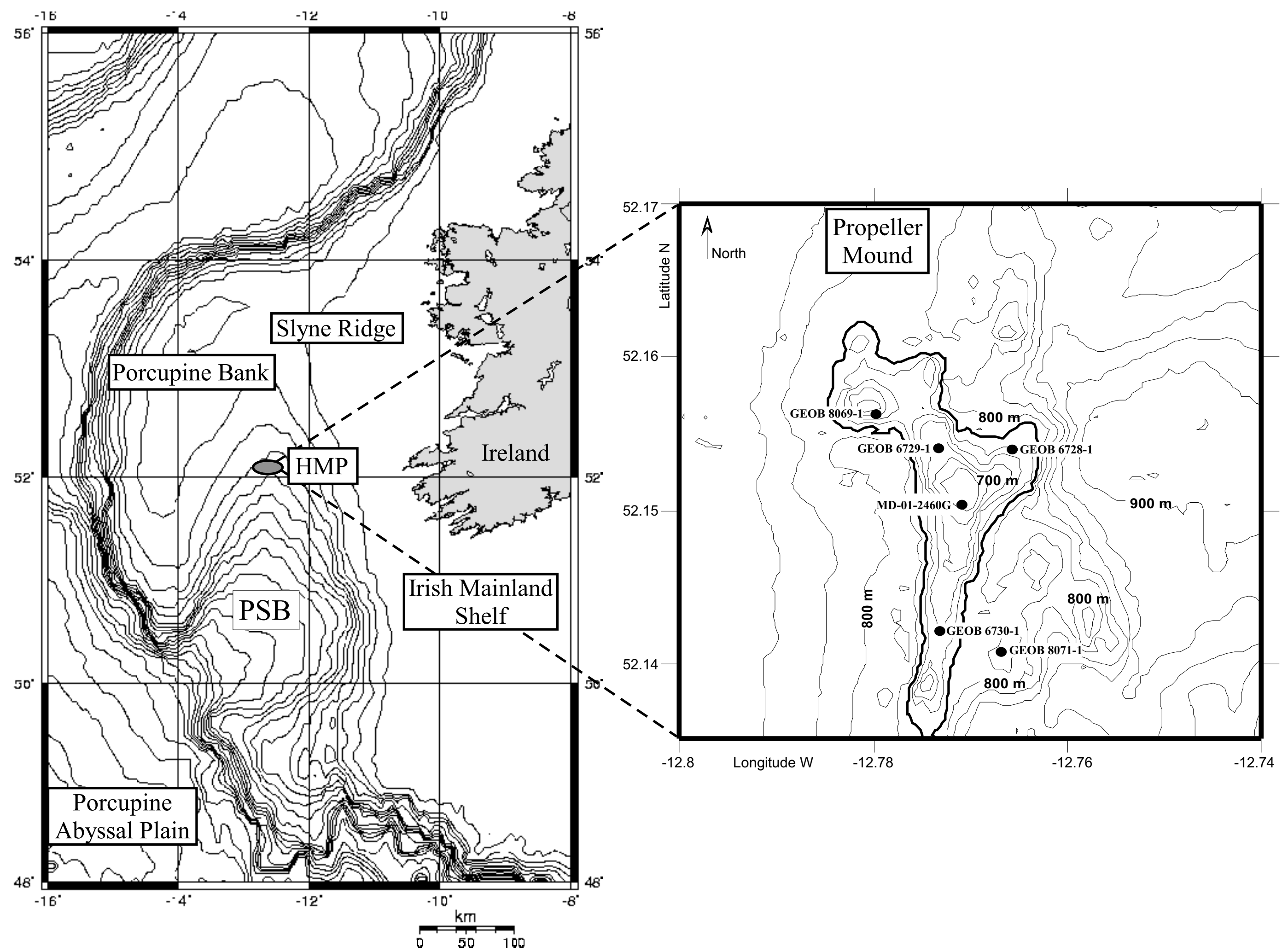

Figure 5.1: Bathymetric map showing the Porcupine Seabight (PSB) southwest of Ireland. Propeller Mound is located in the Hovland Mound Province (HMP) and was mapped during the R/V *Poseidon* cruise POS 265 (Freiwald and shipboard party, 2000). Locations of gravity and box cores indicated. The 780 m water depth contour is indicated in bold to emphasise the outline of Propeller Mound.

been attributed to fluctuations in the intensity of the MOW through glacial and interglacial cycles by Dorschel et al., (2005).

Carbonate Mound Fauna

The fauna associated with carbonate mounds is mainly dependant on environmental forcing in terms of the current regime, food supply and water mass properties. In the PSB the dominant mound building fauna are the azooxanthellate corals *Lophelia pertusa* and *Madrepora oculata.* Their occurrence is apparently constrained by the presence of MOW, which influences bottom current speeds and temperature/salinity in this environment (Freiwald, 2002). In the present day, these corals occur in areas where current speeds are sufficient to prevent the settling of fine particles on their polyps, but not too strong so as to cover the colonies with sand and coarser grains, or knock them over (Wilson, 1979; Mikkelsen et al., 1982; Mortensen et al., 1995; Freiwald and Henrich, 1997; Freiwald, 2002; Roberts et al., 2003). A wide variety of other organisms is associated with these corals such as polychaetes, foraminifers, bryozoa, brachiopods, molluscs, crustaceans, hydroids and echinoids. Usually these organisms settle post mortem on the corals.

DATA AND METHODS

The six gravity cores investigated for this study were collected from Propeller Mound by R/V *Marion-Dufresne*, R/V *Poseidon* and R/V *Meteor*. Their locations are shown in Figure 5.1. All cores were visually described after splitting. Sub-sampling for stable oxygen isotope and grain size analysis was carried out on core MD-01-2460G at 10 cm intervals. Cores GEOB 8069-1 and GEOB 8071-1 were sub-sampled with syringes at 5 cm intervals for stable oxygen isotope analysis. Isotope data for cores GEOB 6728-1, GEOB 6729-1, and GEOB 6730-1 are taken from Dorschel et al., (2005).

Stable isotopes were measured using a Finnigan MAT 251 mass spectrometer at the University of Bremen Isotope Laboratory using phosphoric acid at a constant temperature of 75ºC to evolve CO2 gas. Calibration to PDB was done using a working standard (Burgbrohl CO_2 Gas) which had been calibrated using carbonate standards NBS 18, 19 and 20. The analytical accuracy is about +/- 0.07 ‰ PDB for

$\delta^{18}O$. All isotope measurements were carried out on ~5 specimens of 2 benthic foraminiferal species: either *Cibicides wuellerstorfi* or *Cibicides kullenbergi* from the 125-250 µm grain size fraction.

In addition, depths for biostratigraphic dating were identified on the basis of lithological change in core MD-01-2460G. Sediment samples were prepared for viewing by Scanning Electron Microscope (SEM) according to the technique described by Andruleit (1996). 60 mg of dry bulk sediment was brought into suspension and wet split using a rotary sample divider. This was then filtered onto polycarbonate membranes (Schleicher & Schuell™, 0.4 µm pore size). After drying in an oven at 40°C, a 1 cm^2 piece of the filter was mounted onto an aluminium stub and examined under an SEM at a magnification of 2000x or 3000x. In excess of 500 coccolith specimens were identified in all but a few samples. At least 200 specimens were counted for each sample in order to establish their relative abundance and stratigraphic changes. The coccolithophorid species involved in this study are mainly members of the family Noelaerhabdaceae (including the genera *Gephyrocapsa*, *Pseudoemiliania* and *Reticulofenestra*). The taxonomy of this group is complex, mainly due to the proliferation of species names and morphotypes (e.g., Pujos-Lamy, 1977; Samtleben, 1980; Pujos and Giraudeau, 1993; Bollmann, 1997; Flores et al., 1999). It has been shown that *Gephyrocapsa* species can be distinguished by the combination of morphological parameters such as coccolith size, bridge angle, roundness, and pore-size (e.g., Breheret, 1978; Samtleben, 1980). Additional size criteria have been applied to the entire *Gephyrocapsa* complex (e.g. Matsuoka and Okada, 1990). Most of the morphological characteristics are not inter-correlated and can be easily measured. Hence we have adopted the scheme of Su (1996), Baumann and Freitag, (2004) and Samtleben et al. (own unpubl. data) for the morphological features of gephyrocapsids and reticulofenestrids.

Particle size analysis was carried out on bulk sediment samples from core MD-01-2460G using a Coulter LS2000 Laser Particle Sizer. Freeze dried samples were sieved to remove the 2000 µm size fraction and dispersed with water before organic carbon, carbonate and biogenic silica were removed with excess H_2O_2, HCl, and NaOH respectively. Volume % sand, sortable silt, IRD (ice rafted detritus, >125 μm) and mean sortable silt size were extracted from the results by statistical analysis.

The relative Ca content of the sediment was used as a proxy for the amount of $CaCO_3$ in the cores (Paelike et al., 2001). This was determined using the computer controlled non- destructive CORETEX scanner (Jansen et al., 1998). The cores were scanned at 5 cm intervals, omitting depths with high densities of coral fragments which prevent sufficient coupling between the tool and the core surface for measurement. Measurements were made for 30 s at 20 kV and the collected data were analysed using Toolbox©, the accompanying software. Ca values are displayed as a percentage of total counts of all elements detected by the scanner.

RESULTS

Biostratigraphy

Coccolithophorids were observed in all samples of core MD-01-2460G. Coccoliths of the genus *Gephyrocapsa* are generally the most abundant taxa, with *Calcidiscus leptoporus*, *Coccolithus pelagicus*, *Pseudoemilinia lacunosa*, *Syracosphaera* spp. and a few other species contributing to a minor part of the assemblages. The age ranges of different intervals are shown in Figure 5.2, and reveal the oldest ages recovered for on-mound sediments from Propeller Mound.

The uppermost 0 - 178 cm contain an upper Pleistocene coccolith assemblage, characterised by relatively high numbers, low species diversity and an overwhelming dominance of small- and medium-sized *Gephyrocapsa*. These samples contain neither *Emiliania huxleyi*, which has a first occurrence age (FO) of about 270 ka (Thiersten et al., 1977), nor *Pseudoemiliania lacunosa*. (Thiersten et al., 1977) identified the globally synchronous last occurrence (LO) of *P. lacunosa* at the middle of isotope stage 12. This together with the occurrence of *G. caribbeanica*, *G. margereli* and *G. protohuxleyi*, all are considered here to be extinct forms, point to a stratigraphic datum of this core section between 450 ka and 270 ka, most probably marine isotope stage 9.

A significant increase in the numbers of *G. caribbeanica* between 178 cm and 300 cm, as well as the occurrence of *P. lacunosa* at 300 cm indicate this interval as having been deposited during the mid-Brunhes epoch. The temporal occurrence of *G. carbbeanica* is described in a few recent studies (e.g., Bollmann et al., 1998; Flores et al., 1999; Baumann and Freitag, 2004). This species evolved, increased in abundance and then decreased quickly before becoming extinct within a short time. The species' evolutionary adaptation was likely to be the cause for its dominance during the mid-Brunhes (Bollmann et al., 1998). By correlation with the occurrence of *P. lacunosa* this section can be interpreted as being deposited during isotope stages 13 to 15.

The interval from 328 cm to 1000 cm is characterized by slightly lower abundances of coccoliths in comparison to those observed in the uppermost interval. *G. caribbeanica* remains a dominant species along with small gephyrocapsids, whereas other species (e.g. *C. pelagicus*, *C. leptoporus*, *P. lacunosa*) are recorded only in very low abundances. In some samples, variations of *G. caribbeanica*, e.g. those with closed or nearly closed central areas and very flat bridges, appear to be very similar to some types of *Reticulofenestra productella*, which are characterised by irregular central laths on closed central areas. It is important to note for stratigraphic purposes that *Reticulofenestra asanoi* occurs in rare amounts below 748 cm. The LO of this species is well established (Sato and Takayama, 1992; Su, 1996) as an event occurring at about 0.8 to 0.9 Ma in low and high latitudes. Small-sized *Gephyrocapsa* species dominate the following interval from 1100 cm to 1200 cm. Although some medium-sized species are still present, this section can most probably be assigned to the so-called 'interval of small gephyrocapsids'. Most of the varieties of medium to large *Gephyrocapsa* temporally disappear or greatly reduce their abundance between 1.1 Ma and 0.9 Ma (e.g., Matsuoka and Okada, 1990; Flores et al., 1999).

Rare specimens of *Helicosphaera sellii* occur in the lowest part of the core (below 1200 cm). Although the LO of this species seems to be non-synchronous, its presence in the sediments studied indicate this core section to be older than 1.2 Ma to 1.4 Ma (e.g. Matsuoka and Okada, 1990; Su, 1996), in agreement with the occurrence of large (3.5 - >6 µm) *G. lumina* in the samples. This species differs from *G. oceanica* in having a wider rim with a small or closed central area, whereas its larger size and larger bridge angle make it distinguishable from *G. caribbeanica*. Based on our own biometric results (Samtleben et al., unpubl.), the FO of *G. lumina* is estimated to be at 1.65 Ma and the LO at about 1.25 Ma. Since the average coccolith size of this species has changed through time, the estimated age range of the lowermost section (1200 cm to 1380 cm) of core MD-01-2460G is about 1.4 Ma to 1.5 Ma.

Sedimentology

The amount of bioclastic material (>125 µm) is variable along the core. Based on the amount and relationship of the grains to each other we identified four sedimentary facies (Figure 5.3): (1) mudstone: hemipelagic and pelagic sediment containing less than 10% bioclasts, (2) wackestone: hemipelagic and pelagic matrix supporting more than 10% bioclasts, (3) packstone: grain supported bioclasts with intergranular filling of hemipelagic and pelagic sediments and (4) grainstone: grain supported bioclastic grains with minor infilling of hemipelagic sediment. The Propeller Mound cores GEOB 6728-1, GEOB 6729-1, and GEOB 6730-1 studied by Dorschel et al., (2005), Rüggeberg et al., (in press) and Rüggeberg et al., (submitted) were also subdivided on this basis (Figure 5.4). The facies units are separated from one another by distinct hiatuses indicated by changes in colour and or clast concentration. These hiatuses may be angular, rugose or horizontal (Figure 5.3).

Facies 1: mudstone

This is typically composed of a sandy clayey silt varying in colour from light grey to grey and occasionally olive brown. Units are bioturbated, particularly at the upper and lower boundaries and no sedimentary structures are evident. This facies contains azooxanthelate coral debris accompanied by foraminifera, molluscs and bryozoans. It is one of the main mound facies, and units range in thickness from 5 cm to 1 m.

Facies 2: wackestone

Like Facies 1, it is a sandy clayey silt, though tends to be slightly coarser grained with less clay and more sortable silt present. Sediment is grey to olive grey and olive brown. Bioturbation is common, particularly above and below unit boundaries. Azooanthellate corals are the dominant bioclast in this facies. Foraminifera, molluscs and some bryozoans also occur. This facies is typically between 10 and 150 cm thick; though in some instances it may be as thin as 1 – 2 cm. This is the dominant mound facies.

Facies 3: packstone

This facies is characterised by a high percentage of bioclastic debris of coralline, molluscan and bryozoal material with a light grey to grey sandy to silty matrix. The units are typically thin (2-4 cm) with no bioturbation preserved. Peaks in siliciclastic sand and IRD content roughly correspond to the occurrence of this facies type.

Facies 4: grainstone

This is the thinnest and least common facies unit, averaging 2 cm and occurring in only 3 of the 6 cores (GEOB 8069-1, GEOB 6730-1 and MD-01-2460G). The sediment is grey and composed of bioclastic material, dominated by coral and molluscan debris. Sedimentary features such as clast alignment, reverse grading and angular depositional angles are preserved in some instances. This facies is separated from units above and below by sharp boundaries and no bioturbation.

The bioclastic component of the sediment in all facies is dominated by fragments of the azooxanthellate corals *Lophelia pertusa* and *Madrepora oculata* varying in size from <2 mm up to 7 cm in length. Variability in the corals along the core is evident, with some units containing thickened 'robust' corals, whereas in others corals are 'thin' walled and extremely fragile. The preservation of corals along the core is also variable, with some intervals dominated by highly corroded specimens whereas others contain well preserved coral fragments with their internal structures intact. This observation is irrespective of the species of coral or facies type. Although the volume of bioclastic material is fairly constant along MD-01-2460G, the volume of the various bioclastic components is variable (Figure 5.2).

On the basis of the mean sortable silt size distribution in the decalcified sediments, core MD-01-2460G can be split into an upper (0-898 cm) and a lower (898-1380 cm)

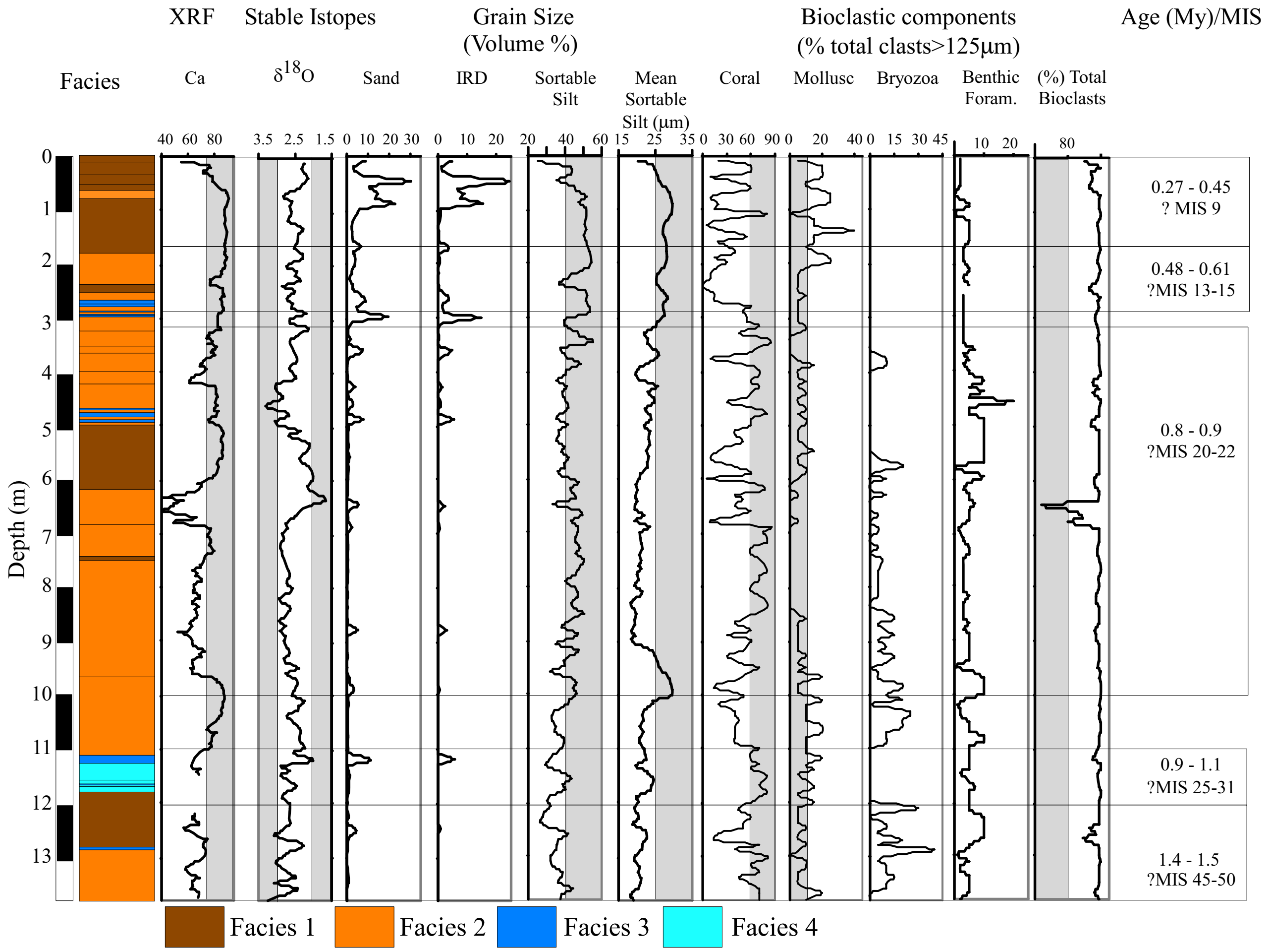

Figure 5.2: Lithology, stratigraphy, Ca content (% Total Counts), benthic oxygen isotope record (‰), non-carbonate grain size analyses and bioclastic components of MD-01-2460G. Facies sub-divisions explained in text. Hiatuses in sedimentary record indicated by horizontal lines in facies column. Glacial and interglacial ranges as identified by Dorschel et al., 2005 indicated in oxygen isotope curve.

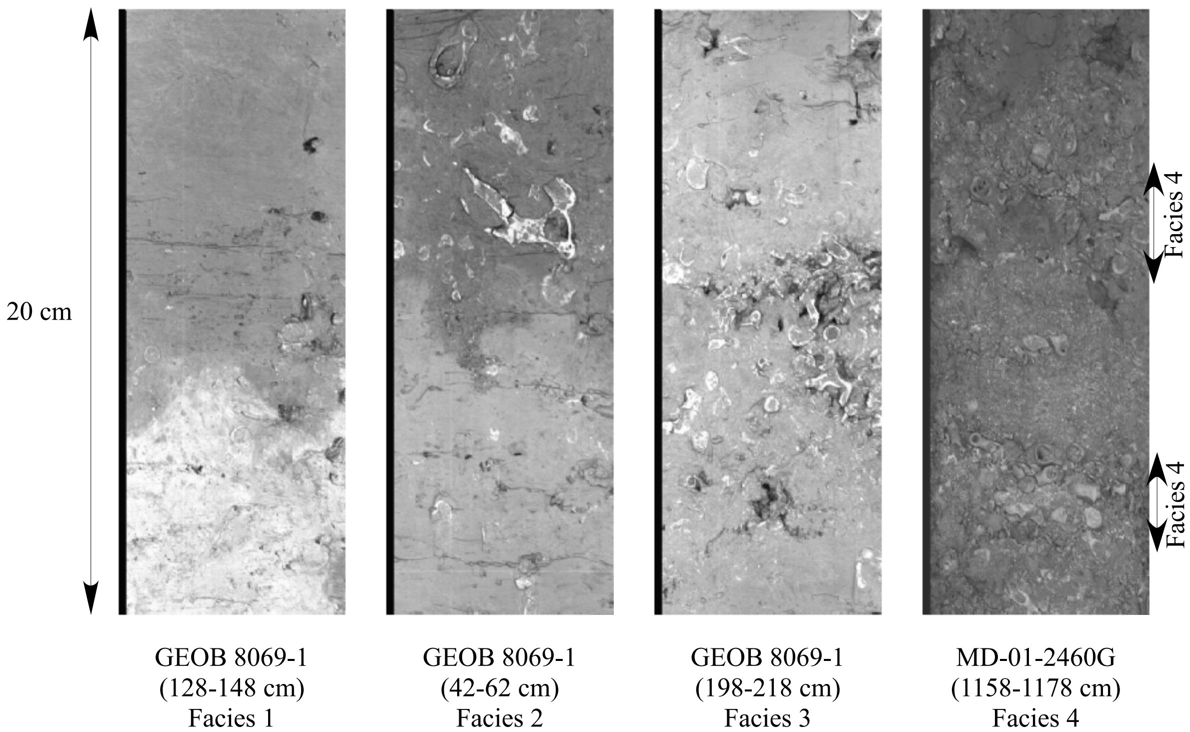

Figure 5.3: Sediment images showing textural variability in on-mound cores representing different stages of mound development. Note distinct hiatuses typical of Facies 1 and 2 between units marked by colour changes and rugosity of boundaries

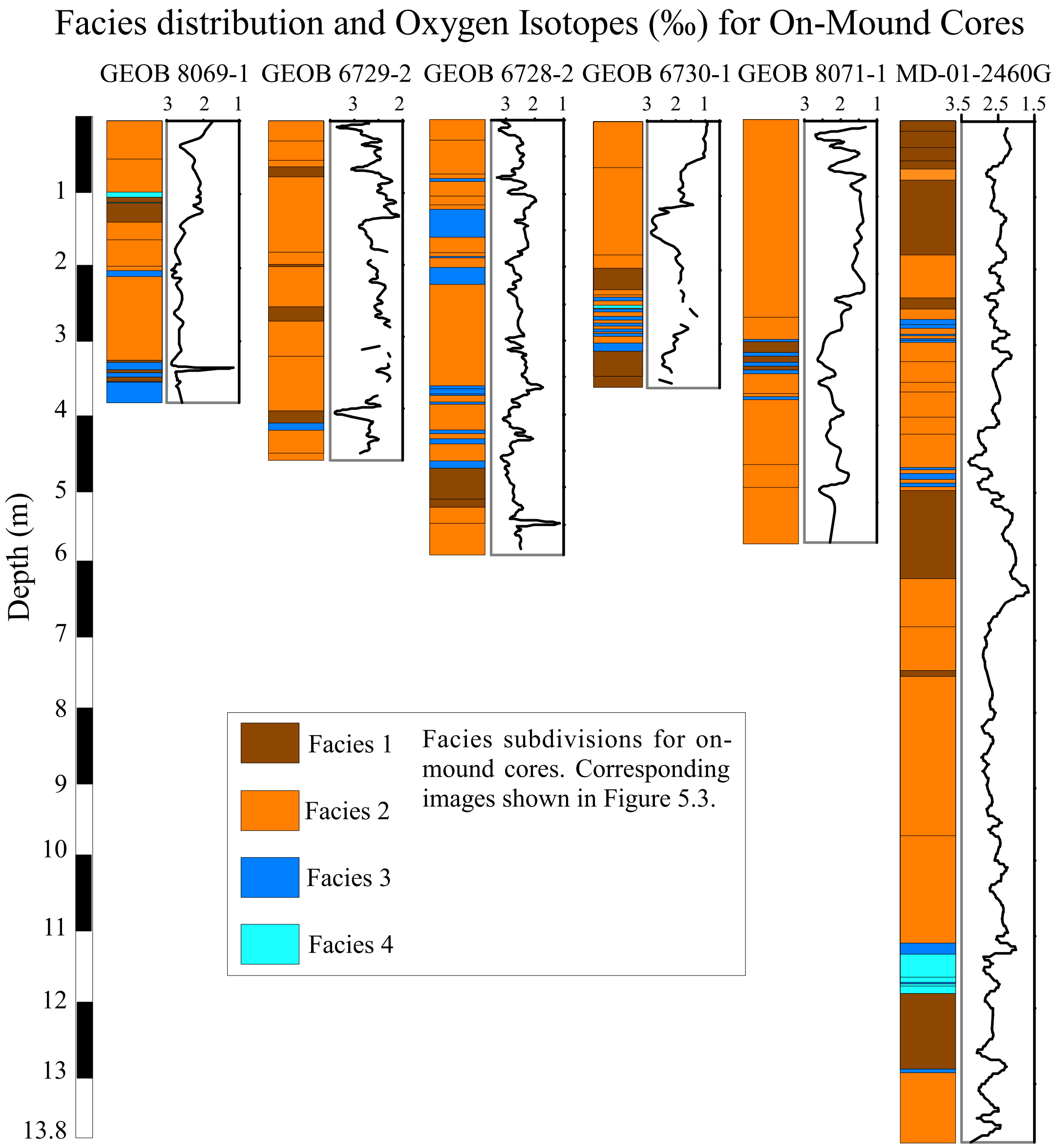

Figure 5.4: Facies subdivisions in all on-mound cores and oxygen isotope data (oxygen isotope data for GEOB cores 6728-2, 6729-2 and 6730-1 from Dorschel et al., 2005. Description of facies discussed in text.

unit. Both units display a coarsening upward trend in mean sortable silt size, with similar size ranges. The upper unit contains more sand than the lower unit, ranging from 0.25 to 30.24 % by volume. The sandiest zones also correspond to intervals of increased IRD (>125 µm). IRD grains can be as large as 6 cm, with IRD enrichments correlating with heavier $\delta^{18}O$ values at some depths (Figure 5.2).

In the upper unit the mean sortable silt size increases gradually from 18.3 µm at 898 cm to a maximum of 29.6 µm at 88 cm before decreasing again to 20.3 µm at the top. The volume of sortable silt roughly follows this pattern. The lower interval also displays an upward increase in mean sortable silt size from 19.1 µm at 1378 cm to 29.6 µm at 988 cm before decreasing again slightly towards 898 cm. The volume of sortable silt is slightly lower than in the upper unit. The sand content is extremely low in this interval, ranging from 0 to 11.36 % by volume. IRD content corresponds to peaks in the sand volume, and the amount present is even lower than in the overlying sediment. Peaks occur at 988 and 1118 cm, and correspond to facies unit boundaries in the sedimentary record.

The Ca content in the core is high, averaging ~70% TC (total counts) with values ranging from 41% TC at 660 cm to 88% TC at 1005 cm. Application of the relationship calculated by Dorschel et al., (2005a) for discrete $CaCO_3$ weight % measurements and XRF intensities for on-mound cores from Propeller Mound gives a range of Ca weight % of 47 – 103% for core MD-01-2460G. Fluctuations in Ca appear more related to the $\delta^{18}O$ record of the cores than to the type of facies subdivision (Figure 5.2).

Benthic foraminiferal stable isotope analysis ($\delta^{18}O$)

Biostratigraphic age ranges indicate that core MD-01-2460G spans marine isotope stages 9, 13 to 15, 20 to 22, 31 to 33 and 45 to 50, however it is not possible to correlate our data with existing isotope curves for the North Atlantic due to the high frequency of hiatuses in the record. In accordance with earlier observations for Propeller Mound cores (Dorschel et al., 2005) predominantly interstadial values (2 to 3‰ PDB) are preserved with only short fluctuations of the curve to truly glacial (>3‰ PDB) or interglacial (< 2‰ PDB) values.

DISCUSSION

As a detailed stratigraphy of Propeller Mound cannot be established, and a correlation between MD-01-2460G and other GEOB cores is not possible due to the fragmented nature of the geological records, the available data do not allow a reconstruction of the paleoceanographic history at the site on a well defined glacial/interglacial or other time scale. As suggested by the stable oxygen isotope data, almost only interstadial sediments are preserved at Propeller Mound. Nevertheless, the repetition of sedimentary facies in the downcore record from Propeller Mound allows some conclusions to be drawn about its development.

The four sedimentary facies identified in the cores can be interpreted as representing changes in the hydrodynamics operating at the mound surface during deposition. The repetition of these facies downcore suggests that particular depositional conditions were also recurring and that the growth of Propeller Mound has not been stable through time. The individual facies may reflect the different stages of carbonate mound development as outlined by Henriet et al., (2002) and De Mol, (2002) using the tropical reef growth strategies of Neumann and Macintyre, (1985).

Facies 1, the mudstone, is interpreted to have been deposited in a low energy environment in which conditions were not suited to prolific coral growth. It is linked to the ‘give up’ phase of Neumann and Macintyre, (1985) and the ‘burial stage’ of Henriet et al., (2002). During the deposition of this unit bottom current speeds were not strong enough to remove sediment from the coral polyps or to transfer food to them, resulting in death.

Facies 2 is the living coral bank stage of Henriet et al., (2002) or ‘keep up’ of Neumann and Macintyre, (1985) as described by De Mol, (2002). Bottom currents are strong enough to provide optimal growth conditions for the mound fauna, and although sediment is being baffled by the coral framework, enough is being removed to avoid siltation of the corals.

Facies 3 and 4 are interpreted to reflect higher energy conditions than Facies 1 and 2, with dense concentrations of bioclastic material and little or no hemipelagic matrix material preserved. In Facies 4, the framework has been destroyed and highly fragmented clasts are all that remain of the original structures. Horizontal alignment of clasts and reverse grading of large coral and molluscan fragments indicate that currents were even strong and persistent enough to sort material. Although deposits like these have been attributed to debris flows in other carbonate environments (Titschak et al., 2005), due to the position of the core at the crest of Propeller Mound it is unlikely to be the cause here. Facies 3 may represent the 'start up' or 'trigger' phase, in which a hard substrate is provided for colonisation by fauna – whereas Facies 4 is a purely destructive stage of mound development preceding faunal re-establishment.

Sedimentary Succession

The repetition of the various facies types is an expression of hydrodynamic variability in the PSB through glacial – interglacial cycles. The age range of core MD-01-2460G covers numerous glacial/interglacial periods, hence we can expect as many shifts in the sedimentary sequence. Dorschel et al., (2005) reasoned that weak bottom currents and a lack of coral growth in the PSB are typical for glacial stages when the advection of MOW to the PSB was strongly reduced or had even ceased. Several such events have occurred through the time period covered by core MD-01-2460G, and we envisage the deposition of mudstones at these times. Considering the fact that the background sedimentation in this region was much higher in glacial compared to interglacial conditions, these Facies 1 sediments should be the most common on Propeller Mound. However, they only account for a minor part of the investigated record. The lack of a true glacial $\delta^{18}O$ throughout the core affirms an argument for the removal of sediments from Propeller Mound.

A certain contribution of IRD is typical for glacial sediments in this part of the North Atlantic. In core MD-01-2460G IRD peaks correlate well with Facies 3 and 4. It is likely that these IRD peaks are not purely the result of individual ice-rafting events, but that these are lag deposits formed by the winnowing of finer sediment from the core associated with the re-establishment of a more vigorous bottom current regime during interglacials. This process has been termed 'deglacial sweeping' by Dorschel et al., (2005), and it has removed many meters of sediment resulting in condensed layers containing coarse material from several millennia (Facies 3 and 4). In turn, these condensed layers can provide the hard substrate for corals to settle on and to grow, thereby baffling hemipelagic sediments and contributing to the vertical accretion of Propeller Mound (Facies 3 to 2). Optimal living conditions for the corals exist under interglacial conditions with a strong MOW advection, as can be seen from the present distribution of cold-water corals at the surface of numerous other carbonate mounds in the Porcupine Seabight (De Mol et al., 2005; Foubert et al., 2005; Huvenne et al., in press). However, the apparent lack of interglacial sediments on Propeller Mound, reflected by the "intermediate" stable oxygen isotope data, is probably due to strong winnowing under the vigorous current regime in such interglacial settings. Thus, continuous mound growth is probably restricted to interstadials, when MOW advection is still strong enough to support coral growth but weak enough to allow for sustained deposition of fine-grained sediments resulting in thick Facies 2 deposits.

The facies development in the six sediment cores from Propeller Mound is marked by repetition of Facies 1 to 4 reflecting mound growth and erosion. The high variability in the facies thickness between the cores is a function of the high spatial variability observed on the present mound surface. This also explains the discontinuous records preserved in each individual core not fitting into a well defined glacial/interglacial time frame.

Faunal Variability

In addition to the sedimentary facies variability, changes in the benthic faunal assemblage also indicate that the hydrodynamic environment was not constant throughout the deposition of the sedimentary record, however, with the most obvious changes occurring on longer time scales than the inferred glacial/interglacial cycles. Faunal variations within the longest core, MD-01-2460G, occur as vertical transitions from one assemblage to another. From surface box core images and ROV video footage it is apparent that there are lateral transitions in faunal distribution occurring on the surface of Propeller Mound today with living coral colonies occurring on the mound flanks and not on its crest (Freiwald and shipboard party, 2000; Freiwald and shipboard party, 2002; Huvenne et al., 2002). Thus, the observed changes downcore could reflect temporal or spatial variability in the environmental setting.

The faunal succession is characterised by a transition from a coral-bryozoan-foraminifera dominated assemblage at the base of the core to a coral-mollusc-foraminifer dominated assemblage at the top. Although, there is no clear link between the relative abundances of the individual organism groups and the sequence of facies in the core, these faunal changes may also be interpreted in terms of changing bottom current conditions. A higher contribution of bryozoans as has been observed at the base of the core and between 8.5 and 11 m core depth could indicate generally lower current speeds, however, still strong enough to support coral growth. Unlike the corals, the bryozoans are more resistant to burial by sediment, and are able to feed in low current speed environments (Holbourne et al., 2002). This interpretation is partly in agreement with the long-term pattern displayed by the mean sortable silt size that indicates that there have been two main periods (below and above 898 cm core depth) of a long-term increase in current strength through these intervals.

Sediment Age and its Implications for Mound Growth Models

The sediment accumulation rates at Propeller Mound are likely to vary between the different facies types and would require a very high-resolution isotopic and biostratigraphic analysis for their determination. The average sediment accumulation rate calculated over the whole length of MD-01-2460G is 1.21 cm/ky, which is comparable to the data of Dorschel et al., (2005).

The new biostratigraphic ages obtained for this longest core through Propeller Mound have a direct implication for the application of an existing carbonate mound growth model in the PSB (Henriet et al., 2002). The base of MD-012460G is dated as being ~1.5 Ma old. Based on seismic studies it is assumed that most of the carbonate mounds in the PSB had initiated growth at the same time during the Pliocene (De Mol et al., 2002; McDonnell and Shannon, 2001). This age has been confirmed during a recent IODP cruise during which Challenger Mound in the eastern Porcupine Seabight had been drilled (Ferdelman et al., 2005) and the mound base has been estimated as having an age of 5.3 Ma. Assuming the same age for the base of Propeller Mound at 280 m below the surface, our data show that the 13.8 m of MD-01-2460G account for a disproportionate amount of Propeller Mound's age. Approximately 30% of the mound's age is contained within the uppermost 5% of the mound's sedimentary record (Figure 5.5).

These data indicate that the vertical growth rate of Propeller Mound must have changed significantly during its development, supporting the sequence of mound growth stages proposed by (Henriet et al., 2002). Following a 'trigger' stage associated with initial mound growth, this model also comprises a 'booster' stage marked by rapid mound growth. The existence of such a 'booster' stage is strongly supported by the age determinations made on core MD-01-2460G and is contained within the unpenetrated depth of the mound. In Henriet´s model the 'booster' stage is followed by a 'coral bank' stage and finally by a 'burial' stage, both of which have lower sediment accumulation rates that the younger stages. The repetition of facies and the number of hiatuses in the core combined with low on-mound sediment accumulation rates in the cored section suggest that Propeller Mound has already passed into the later 'life' stages. Dorschel et al., (in press) calculated higher sedimentation rates for the off-mound environment compared to Propeller Mound, reasoning that Propeller Mound is in a declining stage.

CONCLUSIONS

The sedimentary record of Propeller Mound is regularly interrupted by well defined hiatuses reflecting hydrodynamic changes associated with glacial-interglacial cycles in the PSB. A progression of repeated sedimentary facies and changes in the dominant biological assemblage were able to be identified and related to the intensity of bottom current flow. The repetition of these facies indicates that the 'coral bank stage' on Propeller Mound has repeatedly re-established itself over the last 1.5 Ma to produce sediments of a similar composition despite the large amount of change associated with environmental fluctuations.

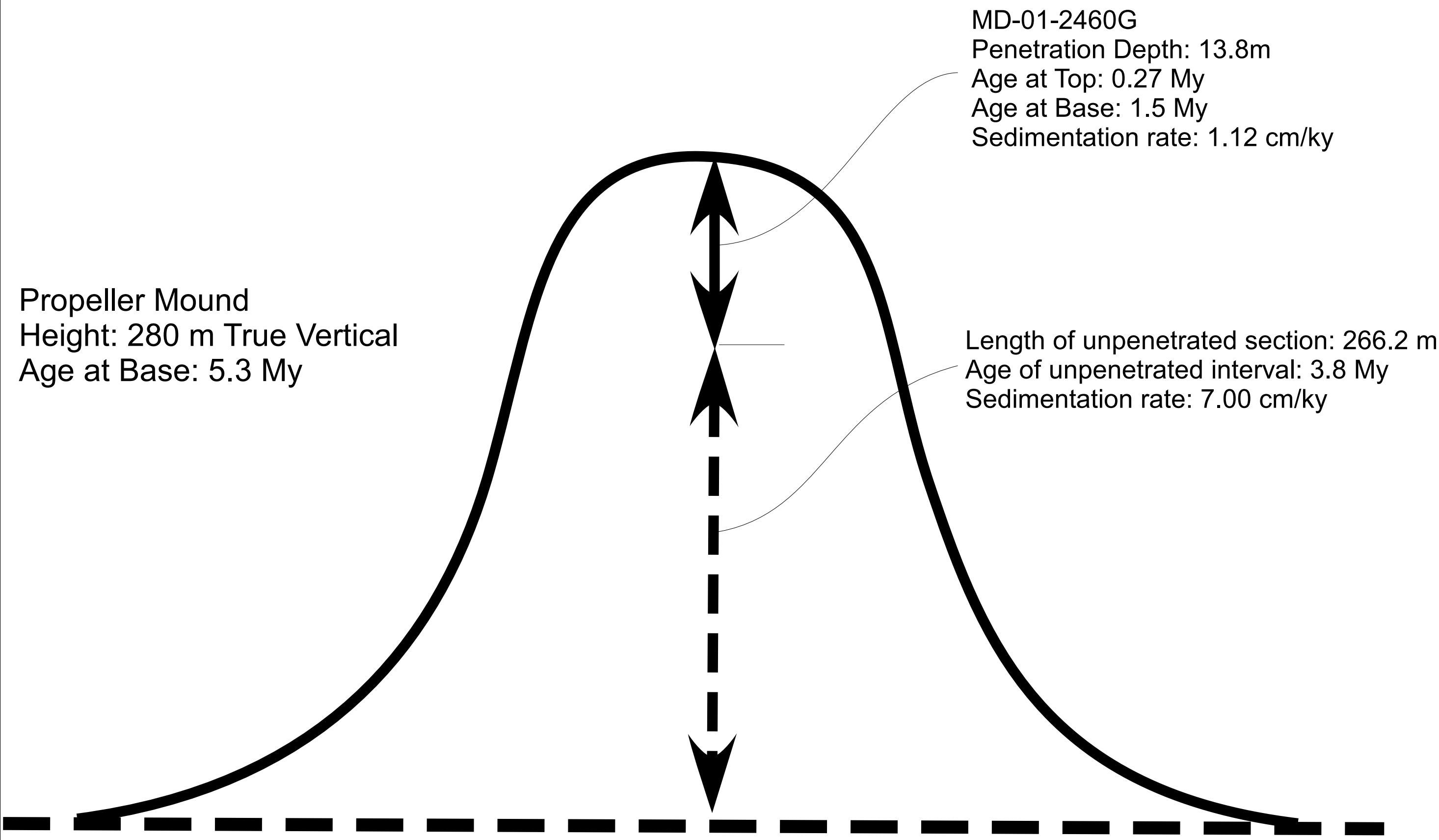

Figure 5.5: Schematic diagram of Propeller mound showing sedimentation rate from MD-01-2460G and inferred sedimentation rate of the unpenetrated section (Base of Propeller Mound to Base of MD-01-2460G) using the onset of mound growth age from IODP 307, 2005.

An average sediment accumulation rate of 1.12 cm/ky was calculated for the cored interval of Propeller Mound and a higher rate of 7 cm/ky was determined for the un-penetrated section. The higher sedimentation rate in the un-cored interval supports mound growth strategy of Henriet et al., (2002) with a rapid 'booster' stage during Propeller Mound's early development and a decrease in rates expected in the later 'coral bank' and 'burial' stages which Propeller Mound has already entered.

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CHAPTER 6: Conclusions

Cores taken from on-mound and off-mound locations in the PSB provide an analysis of hydrodynamic variations and glaciomarine influences on sedimentation in this area for the last 1500 ka. Bottom current speeds vary between glacial and interglacial periods, with sediments deposited during glacials characterised by finer grain sizes than those deposited during interglacials. In the off-mound environment the high resolution record indicates that there may also be significant variability in grain size between different glacial events. We have related this to either the intensity of glaciation or to the proximity and type of ice coverage.

In on-mound sediments variability in current speeds drives the development of the carbonate mounds, controlling the size of sediment deposited and the type and abundance of organisms present. The high frequency of hiatuses, variable thickness of the internal units and the ages preserved in different on-mound cores means that correlation of events is not possible. However, it is possible to identify a repetition of four distinct sedimentary facies in all on-mound cores from Propeller Mound. Each of these facies can be ascribed to a different stage in mound development, from the formation of a hard substrate for larval colonisation, to settlement of larvae and re-establishment of a sediment baffling framework. This is followed by optimal mound growth conditions during periods of moderate current activity, and finally, mound demise with a decrease in current speeds during glacials and subsequent smothering of corals by fine sediment. Our results also provide support for the 'mound booster stage' of Henriet et al. (2002), with a significantly higher sediment accumulation rate calculated for the un-penetrated section of Propeller Mound compared to that of the cored sediments. This unsampled section is thought to be composed of a bioclastic wackestone similar in composition to the dominant mound facies.

Modern surface sediments from Propeller Mound reveal that bottom currents in a small geographic area may be significantly variable. Current focussing at the mound crest and higher current speeds to one side of Propeller Mound result in winnowing, forming a 'lag' of coarser sediment. The seafloor in the lee of the mound is considerably finer grained than the seafloor in the stoss side. This is either due to no coarse sediment being transported to this area, or is an artefact of the lack of winnowing to concentrate coarser grains in this area. The distribution of current speeds over a carbonate mound will constrain where living corals may occur. Speeds that are too high may transport too much sediment and bury the corals, larvae may not settle or the coral framework will break up. Too low current velocities will prevent coral growth through an insufficient food supply and by smothering of polyps by fine sediment.

Further work

Current meter and sediment trap deployment in the carbonate mound areas would provide further information on the range of current speeds and volume of sediment moved by them. High resolution biostratigraphy for on-mound cores may provide a better constraint on the timing and duration of the different depositional events preserved in them. A detailed study of the biological assemblage variations in on-mound sediments would also be beneficial, providing a data set from which environmental and hydrodynamic conditions can be inferred. Furthermore, applying these methods to cores from other mound provinces in the PSB will provide an insight into whether or not the same processes have occurred in all regions and to what extent current speeds are controls on the sedimentary record here. Analysis of the long cores retrieved by ODP in 2005 will be invaluable to solve some of these issues.

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REFERENCES

Akhmetzanov, A.M., van Weering, T.C.E., Kenyon, N.H. and Ivanov, M.K., 1998. Carbonate mounds and reefs at Rockall Troughs and Porcupine Margins. In: B. De Mol (Editor), Geosphere-Biosphere Coupling: Carbonate Mud Mounds and Cold Water Reefs International Conference and Sixth Post Cruise meeting of the Training Through Research Programme, Gent, Belgium, 7-11 February 1998, pp. 45-46.

Akhmetzhanov, A.M. Kenyon, N., Nielsen, T., Habgood, E., Ivanov, M., Henriet, J.P., Shashkin, P., 2001. Deep sea bottom current depositional systems with active sand transport on the North-Eastern Atlantic Margin. In: A.M. Akhmetzhanov and A.E. Suzyumov (Editors), Geological Processes on Deep Water european Margins. International Conference and 10th Anniversary Training Through Research Post Cruise Meeting, 28 January - 3 February 2001, Moscow/Mozhenka, Russia. IOC Workshop Report, 175, UNESCO, 11.

Andruleit, H., 1996. A filtration technique for quantative studies of coccoliths. Micropaleontology, 42: 403-406.

Auffret, G. Zaragosi, S., Dennielou, B., Cortijo, E., Van Rooij, D., Grousset, F., Pujol, C., Eynaud, F., Siegert, M., 2002. Terrigenous fluxes at the Celtic margin during the last glacial cycle. Marine Geology, 188(1-2): 79-108.

Austin, W.E.N. and Evans, J.R., 2000. Benthic foraminifera and sediment grain size variability at intermediate water depths in the Northeast Atlantic during the late Pliocene - early Pleistocene. Marine Geology, 170: 423-441.

Bart, P.J., De Batist, M. and Jokat, W., 1999. Interglacial collapse of the Crary Trough Mouth Fan, Weddell Sea, Antarctica: implications for Antarctic glacial history. Journal of Sedimentary Research, 69: 1276-1289.

Baumann, K.H. and Freitag, T., 2004. Pleistocene fluctuations in the Benguela Current system as revealed by coccolith assemblages. Marine Micropaleontology, 52: 195-215.

Bell, N. and Smith, J., 1999. Coral growing on North Sea oil rigs. Nature, 402: 601.

Beuck, L. and Freiwald, A., 2005. Bioerosion patterns in a deep-water *Lophelia pertusa* (Scleractinia) thicket (Propeller Mound, northern Porcupine Seabight). In: A. Freiwald and J.M. Roberts (Editors), Cold Water Corals and Ecosystems. Springer Verlag, Berlin Heidelberg, pp. 915-936.

Beyer, A., Schenke, H.W., Klenke, M. and Niederjasper, F., 2003. High resolution bathymetry of the eastern slope of the Porcupine Seabight. Marine Geology, 198(1-2): 27-54.

Bollmann, J., 1997. Morphology and biogeography of the genus *Gephryocapsa* coccoliths in Holocene sediments. Marine Micropaleontology, 29: 319-350.

Bollmann, L., Baumann, K.H. and Thiersten, H.R., 1998. Global sdominance of Gephryocapsa coccoliths in the late Pleistocene: selective dissolution, evolution or global environment change. Paleoceanography, 13: 517-529.

Breheret, J.G., 1978. Formes nouvellesquarternaires et actuelles de la famille des *Gephryocapsaceae* (Coccolithophorides). C.R.Acad. Sci., Ser.D, 287: 447-449.

Chachkine, P. and Akhmetzhanov, A., 1998. Subbottom currents on the Porcupine Margin- study by side-scan sonars. In: B. De Mol (Editor), Geosphere-biosphere coupling: Carbonate Mud mounds and Cold Water Reefs. IOC Workshop Report. UNESCO, pp. 30.

Chapman, M.R., Shackleton, N.J. and Duplessy, J.-C., 2000. Sea surface temperature variability during the last glacial-interglacial cycle: assessing the magnitude and pattern of climate change in the North Atlantic. Palaeogeography, Palaeoclimatology, Palaeoecology, 157(1-2): 1-25.

Croker, P.F. and Shannon, P.M., 1995. The petroleum geology of Ireland's offshore basins: Introduction. In: Croker P.F. and S. P.M. (Editors), The petroleum geology of Ireland's offshore basins. Geological Society Special Publication, pp. 1-8.

Davies, A.M. and Xing, J., 2001. Modelling processes influencing shelf edge currents, mixing, across shelf exchange, and sediment movement at the shelf edge. Dynamics of Atmospheres and Oceans, 34: 291-326.

De Mol, B., 2002. Development of coral banks in Porcupine Seabight (SW Ireland): A multidisciplinary approach. PhD Thesis, University of Ghent, Ghent. p. 363.

De Mol, B., Friend, P., Akhmetzhanov, A., Ivanov, M., de haas, H., Belen'kaya, I., Stadnitskaia, A., 1999. Porcupine Seabight: short visit. In: N. Kenyon, M. Ivanov and A. Akhmetzhanov (Editors), Geological Processes on the Northeast Atlantic Margin. IOC Technical Series. UNESCO, pp. 34-47.

De Mol, B. Kozachenko, M., Wheeler, A., Alvarez, H., Henriet, J-P., Olu-LeRoy, K., in press. Therese Mound: a case study of coral bank development in the Belgica Mound Province, Porcupine Seabight. International Journal of Earth Sciences.

De Mol, B., Swennen, R. and Henriet, J.P., 1998. Sedimentology and Geochemical Characteristics of a Core taken from a 'Hovland Mound', Geosphere-Biosphere Coupling: Carbonate Mud Mounds and Cold Water Reefs International Conference and Sixth Post Cruise meeting of the Training Through Research Programme, Gent, Belgium, 7-11 February 1998, pp. 26-27.

De Mol, B., Van Rensbergen, P., Pillen, S., Van Herreweghe, K., Van Rooij, D., McDonnell, A., Huvenne, V., Ivanov, M., Swennen, R, Henriet, J. P., 2002. Large deep-water coral banks in the Porcupine Basin, southwest of Ireland. Marine Geology, 188(1-2): 193-231.

De Stigter, H., de Haas, H. and shipboard party 2001. Cold water corals along the SE and SW Rockall trough margins. PELAGIA cruise 'M2001' Leg 1 of cruise 64PE182, Texel Peterhead 25 June to 9 July, 2001.

Dorschel, B., Hebbeln, D., Rüggeberg, A. and Dullo, C., in press. Carbonate Budget of a cold-water coral carbonate mound: Propeller Mound, Porcupine Seabight. International Journal of Earth Sciences.

Dorschel, B., Hebbeln, D., Rüggeberg, A., Dullo, W.-C. and Freiwald, A., 2005. Growth and erosion of a cold-water coral covered carbonate mound in the Northeast Atlantic during the Late Pleistocene and Holocene. Earth and Planetary Science Letters, 233: 33-44.

Dowdeswell, J.A., Cofaigh, C.O., Taylor, J., Kenyon, N.H., Mienert, J. , Wilken, M., 2002. On the architecture of high-latitude continental margins: the influence of ice-sheet and sea-ice processes in the Polar North Atlantic. In: Dowdeswell J.A.

and C. C. (Editors), Glacier Influenced Sedimentation on High-Latitude Continental Margins. Special Publications. Geological Society, London, pp.33-54.

Faugeres, J.C., Imbert, P., Mezerais, M.L. and Cremer, M., 1998. Seismic patterns of a muddy contourite fan (Vema Channel, South Brazilian Basin) and a sandy distal turbidite deep-sea fan (Cap Ferret system, Bay of Biscay): a comparison. Sedimentary Geology, 115(1-4): 81-110.

Faugeres, J.C., Mezerais, M.L. and Stow, D.A.V., 1993. Contourite drift types and their distribution in the North and South Atlantic Ocean basins. Sedimentary Geology, 82(1-4): 189-203.

Ferdelman, T., Kano, A. and IODP Expedition 307 shipboard party, 2005. IODP Expedition 307 Preliminary Report: Modern Carbonate Mounds, Porcupine Drilling, sites 1316-1318, 25 April - 30 May 2005. pp. 58.

Flores, J.A., Gersonde, R. and Sierro, F.J., 1999. Pleistocene fluctuations in the Agulhas Current Retroflection based on the calcareous plankton record. Marine Micropaleontology, 37: 1-22.

Foubert, A. , Beck, T., Wheeler, A., Opderbecke, J., Grehan, A., Klages, M., Thiede, J., Henriet, J.P., Polarstern ARK-XIX/3a scientific party, 2005. New view of the Belgica Mounds, Porcupine Seabight, NE Atlantic: Preliminary Results from the Polarstern ARK-XIX/3a ROV cruise. In: A. Freiwald and M. Roberts (Editors), Deep-water corals and Ecosystems, Erlangen Earth Conference Series, Springer Verlag, Heidelberg, pp. 403-415.

Frederiksen, R., Jensen, A. and Westerberg, H., 1992. The distribution of the scleractinian coral *Lophelia pertusa* around the Faroe Islands and relation to tidal mixing. Sarsia, 77(2): 157-171.

Freiwald, A. and shipboard party, 2000. Cruise report R.V. Poseidon 265 Faroe Islands - Cork.

Freiwald, A., 2002. Reef-Forming Cold-Water Corals. In: G. Wefer et al. (Editors), Ocean Margin Systems. Springer Verlag, Berlin Heidelberg, pp. 365-385.

Freiwald, A. and Henrich, R., 1997. Anatomy of a deep-water coral reef mound from Stjernsund, West Finnmark, Northern Norway. In: N.P. James and J.A.D. Clarke

(Editors), Cool water Carbonates, SEPM Special Publication 56, Tulsa, pp. 141-161.

Freiwald, A., Huhnerbach, V., Lindberg, B., Wilson, J.B. and Campbell, J., 2002. The Sula Reef Complex, Norwegian shelf. Facies, 47: 179-200.

Freiwald, A. and shipboard party, 2002. Cruise Report RV Poseidon Cruise 292 Reykjavik - Galway.

Freiwald, A. and Wilson, J.B., 1998. Taphonomy of modern, deep, cold temperate water coral reefs. Historical Biology, 13: 37-52.

Freiwald, A., Wilson, J.B. and Henrich, R., 1999. Grounding Pleistocene icebergs shape recent deep-water coral reefs. Sedimentary Geology, 125(1-2): 1-8.

Hall, I.R. and McCave, I.N., 1998. Glacial - interglacial variation in organic carbon burial on the slope of the N.W. European Continental Margin (48˚-50ºN). Progress in Oceanography, 42: 37-60.

Henriet, J.P,, De Mol, B., Pillen, S., Vanneste, M., Van Rooij, D., Versteeg, W., Croker, P.F., Shannon, P.M., Unnithan, V., Bouriak, S., Chachkine, P., Belgica 97 Shipboard Party., 1998. Gas hydrate crystals may help build reefs. Nature, 391(6668): 648-649.

Henriet, J.P., Guidard, S. and Team, O.P., 2002. Carbonate Mounds as a Possible Example for Microbial Activity in Geological Processes. In: G. Wefer et al. (Editors), Ocean Margin Systems. Springer, Berlin Heidelberg, pp. 439-455.

Holbourne, A., Kuhnt, W. and James, N., 2002. Late Pleistocene bryozoan reef mounds of the Great Australian Bight: Isotope stratigraphy and benthic foraminiferal record. Palaeoceanography, 17(3): 1-11.

Hovland, M., Croker, P.F. and Martin, M., 1994. Fault-associated seabed mounds (carbonate knolls?) off western Ireland and north-west Australia. Marine and Petroleum Geology, 11(2): 232-246.

Hovland, M., Mortensen, P.B., Brattegard, T., Strass, P. and Rokoengen, K., 1998. Ahermatypic coral banks off Mid-Norway: Evidence for a link with seepage of light hydrocarbons. Palaios, 13(2): 189-200.

Hovland, M. and Risk, M., 2003. Do Norwegian deep-water coral reefs rely on seeping fluids? Marine Geology, 198(1-2): 83-96.

Hovland, M. and Thomsen, E., 1997. Cold-water corals - Are they hydrocarbon seep related? Marine Geology, 137(1-2): 159-164.

Huvenne, V.A.I., 2003. Spatial geophysical analysis of the Magellan carbonate build-ups and the interaction with sedimentary processes: key to a genetic interpretation?, University of Ghent, Ghent. pp. 285.

Huvenne, V.A.I., Bailey, W.R., Shannon, P.M., Naeth, J., di Primo, R., Henriet, J.P., Horsfield, B., de Haas, H., Wheeler, A., Olu-LeRoy, K., in press. International Journal of Earth Sciences.

Huvenne, V.A.I., Blondel, P. and Henriet, J.P., 2002a. Textural analyses of sidescan sonar imagery from two mound provinces in the Porcupine Seabight. Marine Geology, 189 (3-4): 323-341.

Huvenne, V.A.I., Croker, P.F. and Henriet, J.P., 2002b. A refreshing 3D view of an ancient sediment collapse and slope failure. Terra Nova, 14: 33-40.

Huvenne, V.A.I., De Mol, B. and Henriet, J.P., 2003. A 3D seismic study of the morphology and spatial distribution of buried coral banks in the Porcupine Basin, SW of Ireland. Marine Geology, 198(1-2): 5-25.

Jansen, J.H.F., Van der Gaast, S.J., Koster, B. and Vaars, A.J., 1998. CORTEX, a shipboard XRF-scanner for element analyses in split sediment cores. Mar. Geol., Vol., 151(1-4): 143-153.

Jennings, A.E., Tedesco, K.A., Andrews, J.T. and Kirby, M.E., 1996. Shelf erosion and glacial ice proximity in the Labrador Sea during and after Heinrich events (H-3 or 4 to H-0) as shown by foraminifera. In Andrews J.T., Austin W.E.N., Bergsten H., Jennings A.E. (eds) 1996, Late Quaternary Palaeoceanography of the North Atlantic Margins. Geological Society Special Publication, 111: 29-49.

Johnston, S., Dore, A.G. and Spencer, A.M., 2001. The Mesozoic evoution of the southern North Atlantic region and its relationship to basin development in the south Porcupine Basin, offshore Ireland. In: H.P.D.W. Shannon P.M., Corcoran D.V. (Editor), The Petroleum Exploration of Ireland's Offshore Basins. Geological Society London Special Publication, pp. 237-263.

Jones, S.M., White, N. and Lovell, B., 2001. Cenozoic and Cretaceous transient uplift in the Porcupine Basin and its relationship to a mantle plume. In: H.P.D.W. Shannon

P.M., Corcoran D.V. (Editor), The Petroleum Exploration of Ireland's Offshore Basins. Geological Society London Special Publication, pp. 345-360.

Kenyon, N., Ivanov, M., Akhmetzhanov, A. and New, A., 1998. The current swept continental slope and giant carbonate mounds to the west of Ireland. In: B. De Mol (Editor), Geosphere-biosphere coupling: Carbonate Mud Mounds and Cold Water Reefs. IOC Workshop Report. UNESCO, pp. 24.

Knutz, P., Austin, W.E.N. and Jones, E.J.W., 2001. MIllenial-scale depositional cycles related to British Ice Sheet variability and North Atlanticpaleocirculationsince 45 kyr B.P., Barra Fan, U.K. margin. Palaeoceanography, 16(1): 53-64.

Krylov, O.V., 1998. Distribution of corals and bottom current in the Porcupine Seabight and on the Porcupine Bank, NE Atlantic (from underwater TV and sidescan sonar survey). In: B. De Mol (Editor), Geoshpere-biosphere coupling: Carbonate Mud Mounds and Cold Water Reefs. IOC Workshop Report. UNESCO, pp. 33.

Loewemark, L., Schonfeld, J., Werner, F. and Schafer, P., 2004. Trace fossils as a paleoceanographic tool: evidence from Late Quaternary sediments of the southwestern Iberian margin. Marine Geology, 204(1-2): 27-41.

MacDonald, I.R., Sager, W.W. and Peccini, M.B., 2003. Gas hydrate and chemosynthetic biota in mounded bathymetry at mid-slope hydrocarbon seeps: Northern Gulf of Mexico. Marine Geology, 198: 133-158.

Manighetti, B. and McCave, I.N., 1995a. Depositional fluxes, palaeoproductivity, and ice rafting in the NE Atlantic over the past 30 ka. Paleoceanography, 10(3): 579-592.

Manighetti, B. and McCave, I.N., 1995b. Late glacial and Holocene palaeocurrents around Rockall Bank, NE Atlantic Ocean. Paleoceanography, 10(3): 611-626.

Maslin, M., Shackleton, N. and Pflaumann, U., 1995. Surface water temperature, salinity, and density changes in the northeast Atlantic during the last 45,000 years: Heinrich events, deep water formation, and climatic rebounds. Paleoceanography, 10(3): 527-544.

Masson, D.G., Bett, B. J., Billett, D. S. M., Jacobs, C. L., Wheeler, A. J., Wynn, R. B., 2003. The origin of deep-water, coral-topped mounds in the northern Rockall Trough, Northeast Atlantic. Marine Geology, 194(3-4): 159-180.

Masson, D.G., Howe, J.A. and Stoker, M.S., 2002. Bottom-current sediment waves, sediment drifts and contourites in thr nortern Rockall Trough. Marine Geology, 192: 215-237.

Matsuoka, H. and Okada, H., 1990. Time-progressive morphologic changes inthe genus *Gephryocapsa* in the Quaternary sequence of the tropical IndianOcean, Site 709. Proc. ODP Sci. Results, 115: 255-270.

Mazurenko, L.L., 1998. Fine Sediment from different morphological features of the Porcupine Seabight Basin Floor. In: B. De Mol (Editor), Geosphere-Biosphere Coupling: Carbonate Mud Mounds and Cold Water Reefs International Conference and Sixth Post Cruise meeting of the Training Through Research Programme, Gent, Belgium, 7-11 February 1998, pp. 34-35.

Mazurenko, L.L., 2000. Lithological characteristics of Holocene - Late Pleistocene sediments from carbonate mounds of the Porcupine Seabight basin. In: G. Akhmanov et al. (Editors), Geological Processes on European continental margins International Conference and Eighth Post-Cruise Meeting of the Training-Through-Research Programme. Intergovernmental Oceanographic Commision Workshop Report, Granada, Spain, pp. 6.

McCave, I.N., 1984. Erosion, transport and deposition of fine-grained marine sediments. In: D.A.V. Stow and D.J.W. Piper (Editors), Fine-Grained Sediments: Deep Water Processes and Facies. Geologial Society Special Publications. Blackwell Scientific Publications, Oxford, pp. 35-69.

McCave, I.N., Manighetti, B. and Robinson, S.G., 1995. Sortable silt and fine sediments size/composition slicing: Parameters for paleocurrent speed and palaeoceanography. Paleoceanography, 10(3): 593-610.

McDonnell, A. and Shannon, P.M., 2001. Comparative Tertiary stratigraphic evolution of the Porcupine and Rockall basins. In: H.P.D.W. Shannon P.M., Corcoran D.V. (Editor), The Petroleum Exploration of Ireland's Offshore Basins. Geological Society Special Publication, London, pp. 323-344.

Mikkelsen, N., Erlenkeuser, H., Killingley J, S. and Berger, W.H., 1982. Norwegian corals: radiocarbon and stable isotopes in *Lophelia pertusa.* Boreas, 11(2): 163-171.

Mohn, C., 2000. Über Wassermassen und Strömungen im Bereich des europäischen Kontinentalrandes westlich von Irland. PhD Thesis, University of Hamburg, Hamburg.pp. 133.

Mohn, C., Bartsch, J. and Meincke, J., 2002. Observations of the mass and flow field at Porcupine Bank. Ices Journal of Marine Science, 59: 380-392.

Mohn, C. and Beckmann, A., 2002. Numerical studies on flow amplification at an isolated shelfbreakbank, with application to Porcupine Bank. Continental Shelf Research, 22(9): 1325-1338.

Monty, C.L.V., 1995. The rise and nature of carbonate mud mounds: An introductory actualistic approach. In: C.L.V. Monty, D.W.J. Bosence, P.H. Bridges and B.R. Pratt (Editors), Carbonate Mud Mounds Their Origin and Evolution, International Association of Sedimentologists Special Publication. Blackwell Science, pp. 11-48.

Moore, J.G. and Shannon, P.M., 1995. The Cretaceous succession in the Porcupine basin, offshore Ireland: facies distribution and hydrocarbon potential. In: P.F. Croker and P.M. Shannon (Editors), The Petroleum Geology of Ireland's Offshore Basins. Geological Society Special Publication, pp. 345-370.

Mortensen, P.B., Hovland, M., Brattegard, T. and Farestveit, R., 1995. Deep-water bioherms of the scleractinian coral *Lophelia pertusa* (L) at 64°N on the Norwegian Shelf - Structure and associated megafauna. Sarsia, 80(2): 145-158.

Mortensen, P.B., Hovland, M.T., Fossa, J.H. and Furevik, D.M., 2001. Distribution, abundance and size of Lophelia pertusa coral reefs in mid-Norway in relation to seabed characteristics. Journal of the Marine Biological Association of the United Kingdom, 81(4): 581-597.

Nadeau, M.J., Schleicher, M., Grootes, P.M., Erlenkeuser, H., Gottolong, A., Mous, D.J.W., Sarnthein, M., Willkom, N. 1997. The Leibniz-Labor AMS Facility at the Christian-Albrechts University, Kiel, Germany. Nuclear Instruments & Methods in Physics Research, 123: 22-30.

Naylor, D. and Anstey, N.A., 1987. A reflection seismic study of the Porcupine Basin, offshore west Ireland. Irish Journal of Earth Sciences, 8: 187-210.

Neumann, A.C. and Macintyre, I.G., 1985. Reef response to sealevel rise: keep up, catch up or give up. In: C. Gabrie, J.L. Tuffart and B. Salvat (Editors), 5th International Coral Reef Congress, Tahiti, pp. 105-110.

New, A.L., Barnard, S., Herrmann, P. and Molines, J.M., 2001. On the origin and pathway of the saline inflow to the Nordic Seas: insights from models. Progress in Oceanography, 48(2-3): 255-287.

Paelike, H., Shackelton, N.J. and Roehl, U., 2001. Astronomical forcing in Late Eocene marine sediments. Earth and Planetary Science Letters, 193: 589-602.

Pingree, R.D. and Le Cann, B., 1989. Celtic and Amorican slope and shelf residual currents. Progress in Oceanography, 23: 303-338.

Pingree, R.D. and Le Cann, B., 1990. Structure, strength and seasonality of the slope currents in the Bay of Biscay region. Journal of the Marine Biological Association of the United Kingdom, 70: 857-885.

Powell, R.D., 1990. Glaciomarine processes at grounding-line fans and their growth to ice-contact deltas. In: J.A. Dowdeswell and J.D. Scourse (Editors), Glaciomarine Environments: Processes and Sediments. Geological Society Special Publications, pp. 53-73.

Presti, M., DeSantis, L., Busetti, M. and Harris, P.T., 2003. Late Pleistocene and Holocene sedimentation on the George V Continental Shelf, East Antarctica. Deep Sea Res. Part II Topical Studies in Oceanography, 50(8-9): 1441-1461.

Prins, M.A., Bouwer, L.M., Beets, C.J., Troelstra, S.R. and G.J., W., 2002. Ocean circulation and iceberg discharge in the glacial North Atlantic: Inferences from unmixing of sediment sizedistributions. Geology, 30(6): 555-558.

Pujos, A. and Giraudeau, J., 1993. Reparation des Noelrhabdaceae (nanofossiles calcaires) dans e Quarternaire moyen et superieur des oceans Atlantic et Pacifique. Oceanologica Acta, 16(4): 349-362.

Pujos-Lamy, A., 1977. *Emiliana* et *Gephryocapsa* (Nannoplancton calcaire): Biometrie et interet biostratigraphique dans le Pleistocene superieur marin des Acores. Rev. Espanola de Micropaleontol., 9: 69-84.

Ratmeyer, V. and shipboard party, 2006. Report and preliminary results of RV METEOR cruise M61/3, Cork - Ponta Delgada, 04.06. - 21.06.2004. Berichte, Fachbereich Geowissenschaften, Universität Bremen, no. 247, 6 pages.

Rice, A.L., Billett, D.S.M., Thurston, M.H. and Lampitt, R.S., 1991. The Institute of Oceanographic Sciences Biology programme in the Porcupine Seabight: background and general introduction. Journal of the Marine Biological Association of the United Kingdom, 71: 281-310.

Rice, A.L., Thurston, M.H. and Bett, B.J., 1994. The Iosdl Deepseas Program - Introduction and photographic evidence for the presence and absence of a seasonal input of phytodetritus at contrasting abyssal sites in the Northeastern Atlantic. Deep-Sea Research Part I-Oceanographic Research Papers, 41(9): 1305-1320.

Rice, A.L., Thurston, M.H. and New, A.L., 1990. Dense aggregations of the hexactinellid sponge, *Pheronema carpenteri*, in the Porcupine Seabight (northeast Atlantic Ocean), and possible causes. Progress in Oceanography, 24: 179-196.

Richter, T.O., Lassen, S., van Weering, T.C.E. and de Haas, H., 2001. Magnetic susceptibility patterns and provenance of ice-rafted material at Feni Drift, Rockall Trough: implications for the history of the British-Irish ice sheet. Marine Geology, 173(1-4): 37-54.

Roberts, J.M., Long, D., Wilson, J.B., Mortensen, P.B. and Gage, J.D., 2003. The cold-water coral *Lophelia pertusa* (Scleractinia) and enigmatic seabed mounds along the north-east Atlantic margin: are they related? Marine Pollution Bulletin, 46(1): 7-20.

Robinson, A.J. and Canham, A.C., 2001. Reservoir characteristics of the Upper Jurassic sequence in the 35/8-2 discovery, Porcupine Basin. In: H.P.D.W. Shannon P.M., Corcoran D.V. (Editor), The Petroleum Exploration of Ireland's Offshore Basins. Geological Society London, Special Publications, pp. 301-321.

Robinson, S.G., Maslin, M.A. and McCave, I.N., 1995. Magnetic susceptibility variations in Upper Pleistocene deep-sea sediments of the NE Atlantic: implications for ice rafting and palaeocirculation at the last glacial maximum. Paleoceanography, 10(2): 221-250.

Rüggeberg, A., Dorschel, B., Dullo, W.C., Hebbeln, D., submitted. Benthic foraminiferal assemblages from Propeller Mound, Northern Porcupine Seabight. Marine Micropaleontology.

Rüggeberg, A., Dorschel, B., Dullo, W.C., Hebbeln, D., 2005. Sedimentary patterns in the vicinity of a carbonate mound in the Hovland Mound province, northern Porcupine Seabight. In: Freiwald, A. and Roberts, M (eds), Cold water Corals and Ecosystems, Erlangen Earth Conference Series. Springer Verlag, Heidelberg. pp 87-112.

Rüggeberg, A., Dullo, W.C., Dorschel, B., Hebbeln, D., in press. Environmental changes and growth history of a cold-water carbonate mound (Propeller Mound, Porcupine Seabight). International Journal of Earth Sciences.

Samtleben, C., 1980. Die Evolution der Coccolithophoriden-Gattung *Gephryocapsa* nach Befunden im Atlantik. Palaeont. Z., 54: 91-127.

Saoutkine, A., 1998. Influence of surface water temperature oscillations on the development of deep-water coral build ups in the Porcupine Basin (North Atlantic). In: B. De Mol (Editor), Geosphere-Biosphere Coupling: Carbonate Mud Mounds and Cold Water Reefs International Conference and Sixth Post Cruise meeting of the Training Through Research Programme, Gent, Belgium, 7-11 February 1998, pp. 25-26.

Sato, T. and Takayama, T., 1992. A statigraphical significant new species of calcareous nannofossil *Reticulofenestra asanoi*. In: K. Ishizaki and T. Saito (Editors), Centenary off Japanese Micropaleontology. Terra Scientific, Tokyo, pp. 457-460.

Schoenfeld, J., 2002a. A new benthic foraminiferal proxy for near-bottom current velocities in the Gulf of Cadiz, northeastern Atlantic Ocean. Deep-Sea Research Part I-Oceanographic Research Papers, 49(10): 1853-1875.

Schoenfeld, J., 2002b. Recent benthic foraminiferal assemblages in deep high-energy environments from the Gulf of Cadiz (Spain). Marine Micropaleontology, 44(3-4): 141-162.

Schoenfeld, J. and Zahn, R., 2000. Late Glacial to Holocene history of the Mediterranean Outflow. Evidence from benthic foraminiferal assemblages and stable isotopes at the Portuguese margin. Palaeogeography Palaeoclimatology Palaeoecology, 159(1-2): 85-111.

Scourse, J.D., Hall, I.R., McCave, I.N., Young, J.R. and Sugdon, C., 2000. The origin of Heinrich Layers: evidence from H2 for European precursor events. Earth and Planetary Science Letters, 182: 187-195.

Shannon, P.M., 1991. The development of Irish offshore sedimentary basins. Journal of the Geological Society, London, 148: 181-189.

Shannon, P.M., Williams, B.P.J. and Sinclair, I.K., 1995. Tectonic controls on Upper Jurrasic to Lower Cretaceous reservoir architecture in the Jeanne d'Arc Basin, with some comparisons from the Porcupine and Moray Firth Basins. In: P.F. Croker and P.M. Shannon (Editors), The Petroleum Geology of Ireland's Offshore Basins. Geological Society Special Publication, pp. 467-490.

Sinclair, I.K., 1995. Sequence stratigraphic response to Aptian - Albian rifting in conjugate margin basins: a comparison of the Jeanne d'Arc Basin, offshore Newfoundland, and the Porcupine Basin, offshore Ireland. In: R.A. Scrutton, M.S. Stoker, G.B. Shimmield and A.W. Tudhope (Editors), The Tectonics, Sedimentation and Palaeoceanographyof the North Atlantic Region. Geological Society Special Publication, pp. 29-49.

Snoeckx, H., Grousset, F., Revel, M. and Boelaert, A., 1999. European contribution of ice-rafted sand to Heinrich layers H3 and H4. Mar. Geol., 158(1-4): 197-208.

Spielhagen, R.F., Erlenkeuser, H. and Siegert, M., 2005. History of freshwater runoff across the Laptev Sea (Arctic) during the last deglaciation. Global and Planetary Change, 48 (1-3): 187-207

Stevens, R.L., 1990. Proximal and distal glaciomarine deposits in southwestern Sweden: contrasts in sedimentation. In: J.A. Dowdeswell and J.D. Scourse (Editors), Glaciomarine Environments: Processes and Sediments. Geological Society Special Publications No. 53, pp. 307-316.

Stoker, M.S., Nielsen, T., van Weering, T.C.E. and Kuijpers, A., 2002. Towards an understanding of the Neogene tectonostratigraphic framework of the NE Atlantic margin between Ireland and the Faroe Islands. Marine Geology, 188(1-2): 233-248.

Su, X., 1996. Development of late Tertiary and Quaternary coccolith assemblages in the northeast Atlantic. GEOMAR Report, pp. 48.

Sumida, P. and Kennedy, R., 1998. Biological Data. In: N.H. Kenyon, M.K. Ivanov and A.M. Akhmetzhanov (Editors), Cold water carbonate mounds and sediment transport on the Northeast Atlantic margin *IOC Technical Series No. 52*. UNESCO, pp. 102-106.

Swennen, R., Cronin, B.T., Ivanov, M., Kozlova, E., Wheeler, A. J., Akhmetzhanov, A.M., Sautkin, A., Van Rooij, D., Zaragosi, S., Mazurenko, L., Degryse, C., Sumida, P., Satur, N., Kennedy, R., Akhmanov, G., Belen'kaya, I., Pillen, S., Naumov, Y., Stadnitskaya, A., De Mol, B., Balashova, A., Saprykina, A. 1998. Bottom sampling results. In: N. Kenyon, M. Ivanov and A.M. Akhmetzhanov (Editors), Cold Water Carbonate Mounds and Sediment Transport on the Northeast Atlantic Margin. IOC Technical Series. UNESCO, Paris, pp. 59-97.

Tate, M.P., 1993. Structural framework and tectonostratigraphic evolution of the Porcupine Seabight Basin, offshore western Ireland. Marine and Petroleum Geology, 10: 95-123.

Teichert, C., 1958. Cold and deep-water coral banks. Bulletin of the American Association of Petroleum Geologists, 42(5): 1064-1082.

Thierstein, H.R., Geitzenauaer, K.R., Molfino, B. and Shackelton, N.J., 1977. Global synchroneity of late Quaternary coccolith datum levels: Validation by oxygen isotopes. Geology, 5: 400-404.

Thomas, E., Booth, L., Maslin, M. and Shackleton, N.J., 1995. Northeastern Atlantic benthic foraminifera during the last 45,000 years - Changes in productivity seen from the bottom up. Paleoceanography, 10(3): 545-562.

Titschak, J., Bromley, R.G. and Freiwald, A., 2005. Plio-Pleistocene cliff-bound wedge-shaped warm-temperate carbonate deposits from Rhodes (Greece): Sedimentology and Facies. Sedimentary Geology, 180(1-2): 29-56.

Trasvina-Castro, A. Gutierrez de Velasco, G., Valle-Levinson, A., Gonzalez-Armas, R., Muhlia, A., Cosio, M.A., 2003. Hydrographic observations of the flow in the vicinity of a shallow seamount top in the Gulf of California. Estuarine, Coastal and Shelf Science, 57: 149-162.

Turnewitsch, R., Reyss, J.L., Chapman, D.C., Thomson, J. and Lampitt, R.S., 2004. Evidence for a sedimentary fingerprint of an asymmetric flow field surrounding a short seamount. Earth and Planetary Science Letters, 222: 1023-1036.

Van Aken, H.M., 2000. The hydrography of the mid-latitude Northeast Atlantic Ocean II: The intermediate water masses. Deep Sea Research, 47: 789-824.

Van Gaever, S., Vanreusel, A., Hughes, J.A., Bett, B. and Kiriakoulakis, K., 2004. The macro- and micro-scale patchiness of meiobenthos associated with the Darwin Mounds (north-east Atlantic). Journal of the Marine Biological Association of the United Kingdom, 84(3): 547-556.

Van Rooij, D., 2004. An integrated study of Quaternary sedimentary processes on the eastern slope of the Porcupine Seabight, SW of Ireland. PhD. Thesis, University of Ghent, Ghent, 330 pp.

Van Rooij, D., Blamart, D., Wheeler, A., Richter, T., Henriet, J.P., Kozachenko, M., in press. Quaternary drift sediment dynamics in the Belgica Mound Province, Porcupine Seabight: ice-rafting events and contour current processes. International Journal of Earth Sciences.

Van Rooij, D., Blamart, D. and Unnithan, V., 2001. Cruise Report MD123-Geosciences: Leg 2, part GEOMOUND. Porcupine Basin and Rockall Trough, off Western Ireland, September 7-11, 2001.

Van Rooij, D., De Mol, B., Huvenne, V., Ivanov, M. and Henriet, J.P., 2003. Seismic evidence of current-controlled sedimentation in the Belgica mound province, upper Porcupine slope, southwest of Ireland. Marine Geology, 195: 31-53.

van Weering, T.C.E., de Haas, H., de Stigter, H.C., Lykke-Andersen, H. and Kouvaev, I., 2003. Structure and development of giant carbonate mounds at the SW and SE Rockall Trough margins, NE Atlantic Ocean. Marine Geology, 198(1-2): 67-81.

Vermeulen, N.J., 1996. Hydrography, Surface Geology and Geomorphology of the Deep Water Sedimentary Basins to the West of Ireland. Atlantic Irish Regional Survey Publication. Marine Sciences Series, (2): pp. 41.

Weaver, P.P.E., Wynn, R.B., Kenyon, N.H. and Evans, J., 2000. Continential margin sedimentation, with special reference to the north-east Atlantic margin. Sedimentology, 47(239-256).

Weltje, G.J. and Prins, M.A., 2003. Muddled or mixed? Inferring palaeoclimate from size distributions of deep-sea clastics. Sedimentary Geology, 162: 39-62.

Weninger, B., Joeris, O. and Danzeglocke, U., 2004. Calpal: Cologne Radiocarbon Calibration and Paleoclimate Research Package, Cologne.

Wheeler, A., Degryse, C., Limonov, A. and Kenyon, N., 1998a. OREtech sidescan sonar data - The Northern Porcupine Seabight. In: N. Kenyon, M. Ivanov and A. Akhmetzhanov (Editors), Cold water carbonate mounds and sediment transport on the Northeast Atlantic margin. Intergovernmental Oceanographic Commision technical series. UNESCO, pp. 40-54.

Wheeler, A.J., Cronin, B.T., Kenyon, N.H., Satur, N., Sautkin, A., Devoy, R.J. 1998b. Channel Architecture and activity in the Gollum Channel, Porcupine Seabight. In: B. De Mol (Editor), Geosphere Biosphere Coupling: Carbonate Mud Mounds and Cold Water Reefs. IOC Workshop Report. UNESCO, Paris, pp. 30-31.

White, M., 2003. Comparison of near seabed currents at two locations in the Porcupine Seabight- implications for benthic fauna. Journal of the Marine Biological Association of the United Kingdom, 83: 682-686.

White, M., in press. Benthic dynamic at the carbonate mound regions of the Porcupine Seabight continental margin. International Journal of Earth Sciences.

White, M., Mohn, C. and Orren, M.J., 1998. Nutrient distributions across the Porcupine Bank. Ices Journal of Marine Science, 55: 1082-1094.

Wilson, J.B., 1979. "Patch" development of the deep-water coral *Lophelia pertusa* (L.) on the Rockall bank. Journal of the Marine Biological Association of the United Kingdom, 59: 165-177.

Wilson, J.B. and Herbon, C.V., 1998. Deep-water corals and associated faunas on carbonate mounds, north slope of Porcupine Bank and the south east slope of Rockall Bank. In: B. De Mol (Editor), Geosphere-Biosphere Coupling: Carbonate Mud Mounds and Cold Water Reefs International Conference and Sixth Post Cruise meeting of the Training Through Research Programme, Gent, Belgium, 7-11 February 1998, pp. 43-44.

Yokokawa, M. and Franz, S., 2002. Changes in grain size and magnetic fabric at Blake-Bahama Outer Ridge during the late Pleistocene (marine isotope stages 8-10). Marine Geology, 189: 123-144.