Contourite Sands in the Gulf of Cadiz: Characterisation, Controls and Wider Implications for Hydrocarbon Exploration.

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ABSTRACT

This study uses an extensive data-set from a sand-rich contourite depositional system located in the Gulf of Cadiz. Newly acquired data, targeting a modern contourite sandy depositional system in the eastern Gulf of Cadiz, has been integrated with historical data, including a seismic survey over a Pliocene mixed system in the northern Gulf of Cadiz. Seismic, core and sediment analysis has been used to assess the controls on the system, and characterise the sediments. The presented study gives a new complete view of past circulation of the Mediterranean Outflow Water and contourite deposition in the eastern Gulf of Cadiz over the upper, mid and lower slope. It also identifies a mixed system in the Pliocene section of the northern Gulf of Cadiz. This allows us to make the following contributions to the field;

1. A new model from Quaternary evolution of the eastern sandy contourites, and Pliocene evolution of a sandy mixed system the northern Gulf of Cadiz.
2. A detailed examination of the sand facies and sediment of the Gulf of Cadiz and a new set of contourite sand facies models proposed.
3. A thorough examination of the controls on contourite formation, and their integration in a sequence stratigraphic framework.
4. A review of the hazards bottom currents pose to deep water exploration, and the reservoir potential of contourite sands and other facies.

The Gulf of Cadiz provides a good modern day analogue for contourite sands. They show various facies and sedimentological characteristics that are tied to depositional processes. They are also highly cyclic in nature, on a variety of time scales. If they can be positively identified in the subsurface, they have the capacity to make potential hydrocarbon reservoirs. The facies and sedimentological models presented here, and their integration into a sequence stratigraphic model will aid the positive identification of these deposits in the future.

ACKNOWLEDGEMENTS

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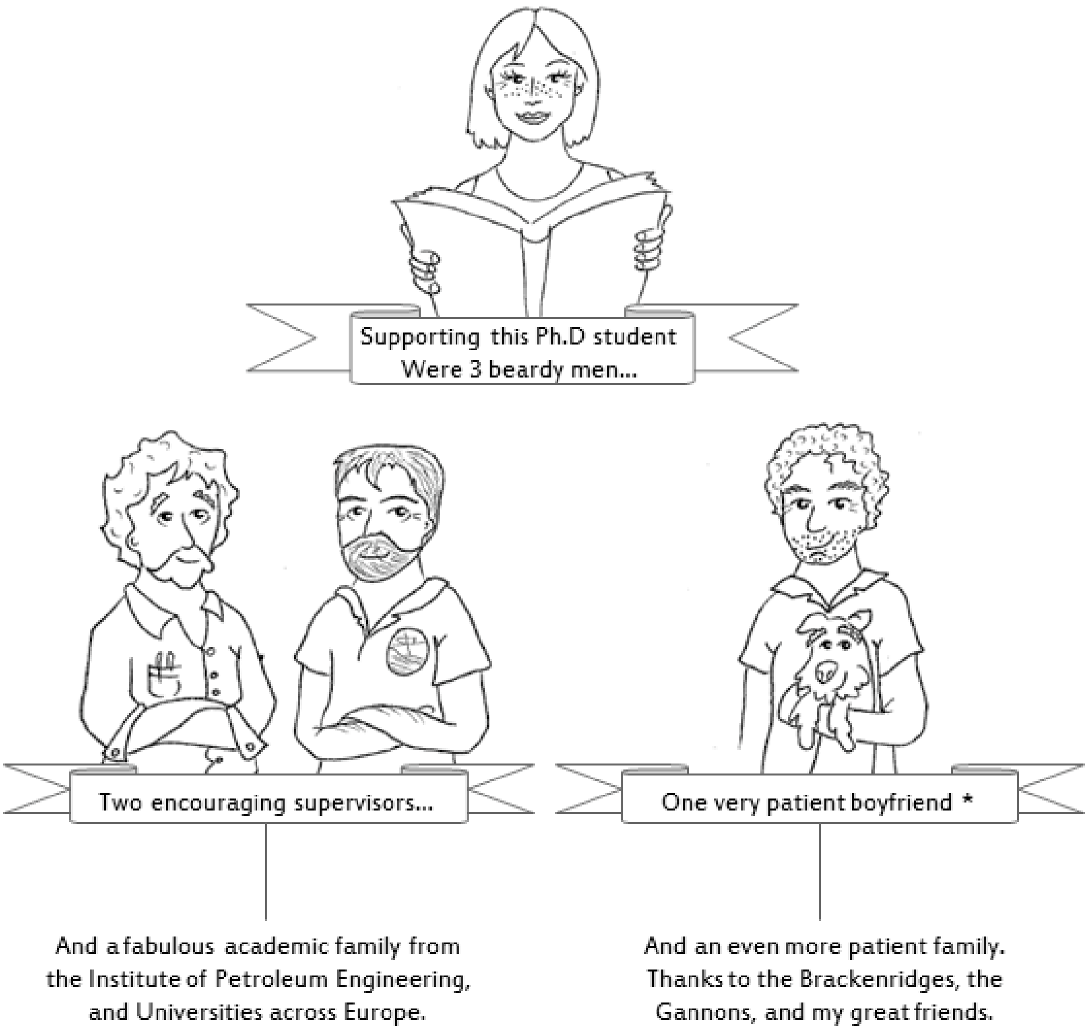

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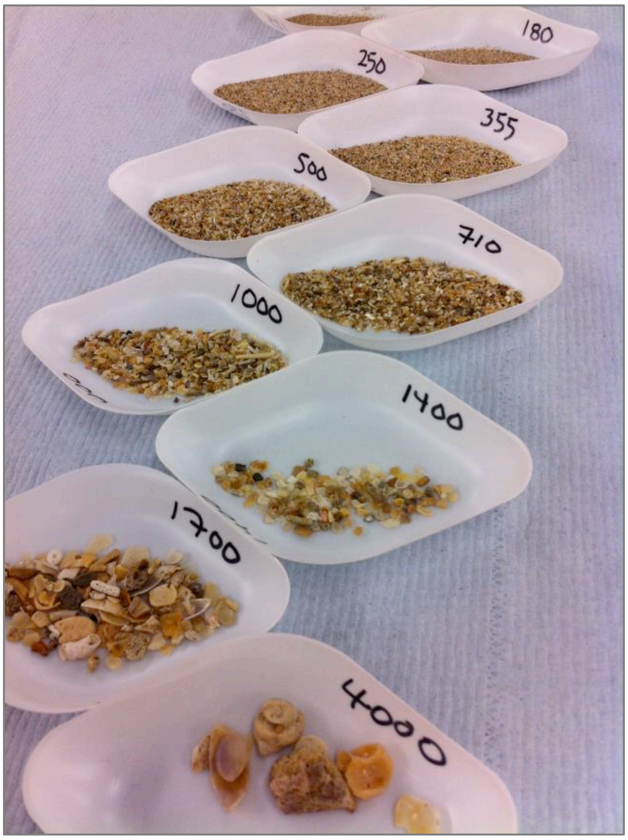
List of Abbreviations

AABW	Antarctic Bottom Water
AAIW	Antarctic Intermediate Water
AI	Atlantic Inflow
ASW	Atlantic Surface Water
CDS	Contourite Depositional System
HST	Highstand Systems Tract
LST	Lowstand Systems Tract
MOW	Mediterranean Outflow water
NACW	North Atlantic Central Water
NADW	North Atlantic Deep Water
TST	Transgressive Systems Tract

Introduction



1 Introduction

This study tackles numerous aspects of sand-dominated contourite depositional systems, focusing on the Gulf of Cadiz, but also considering the wider published data from systems around the globe. This research has four key aims: 1) To present a new detailed understanding of the Gulf of Cadiz sandy contourites offshore Spain. This will focus on the recent (Quaternary) contourite sands in the eastern Gulf of Cadiz and a Pliocene mixed system in the north; 2) Using the Gulf of Cadiz contourite depositional system as an analogue, the contourite sand facies will be characterised both sedimentologically and acoustically to aid future identification of these deposits along other continental margins and in the geological record; 3) The broader controls on contourite deposition are discussed and a new model for sequence stratigraphy outlined to aid prediction of further contourite sand deposits in the subsurface and; 4) The above information will be applied to assess the economic potential of contourites with a focus on contourite sand reservoir potential. Understanding the geometries and internal architecture that are observed in sand-rich contourite deposits will have important applications for hydrocarbon exploration, reservoir modelling and production.

Contourites form an important element of sedimentation along continental margins (Rebesco and Camerlenghi 2008). They are features generated by semi-continuous bottom currents that distribute energy and nutrients around the oceans. These bottom currents can generate large erosional and depositional features on the sea bed, with sediment accumulations reaching many kilometres in length and many hundreds of metres in thickness. Such deposits hold important information on past climatic conditions, as preserved in nannofossils, foraminifera and minerals. Ever improving geophysical techniques, combined with increased publicity and coordination of research, has led to the discovery of many new contourites in recent years. A number of special volumes have been published to help progress contourite research (Stow and Faugères 1998; Stow et al. 2002c; Viana and Rebesco 2007; Hernández-Molina et al. 2011b) and the first text book was released in 2008 (Rebesco and Camerlenghi 2008). Numerous IODP and ODP Expeditions have now specifically targeted contourite accumulations to answer questions on palaeoceanography and palaeoclimate (Odonnell et al. 2007; Fulthorpe et al. 2010; Expedition 342 Scientists 2012; Expedition 339 Scientists 2012). In addition to this, the recent realisation that bottom currents have the capacity to deposit significant accumulations of sands has sparked interest from hydrocarbon explorationists Shanmugam 2006; Viana et al. 2011a; Stow et al. 2011a). Despite growing interest, a lack of clear diagnostic criteria at core scale, and a poor understanding of deep water circulation in the past, has made the identification of contourite sand in the subsurface problematic. This is the main driver for this research.

The study area is located in the Gulf of Cadiz (Fig. 1.1). Here, the largest known deep water sandy contourite deposit is located in the eastern Gulf of Cadiz. It covers an estimated area of 4000 km^2 and industry boreholes suggest that there is over 800 m of sand-rich contourite section (Antich et al. 2005). Preliminary analyses of selected cores revealed clean sands that would potentially yield excellent reservoir characteristics on burial. It therefore provides an ideal location for the study of contourite sands, their characteristics and controls. These contourite sands form part of a much larger contourite depositional system in the Gulf of Cadiz (Fig. 1.1), for which a huge database now exists (surface and subsurface). This database has been expanded with targeted data acquisition over sand-dominated regions throughout the course of this research through the Spanish research CONTOURIBER-1 and MOWER projects, and the Intergrated Ocean Drilling Program (IODP Expedition 339). This will be the main study area of the thesis.

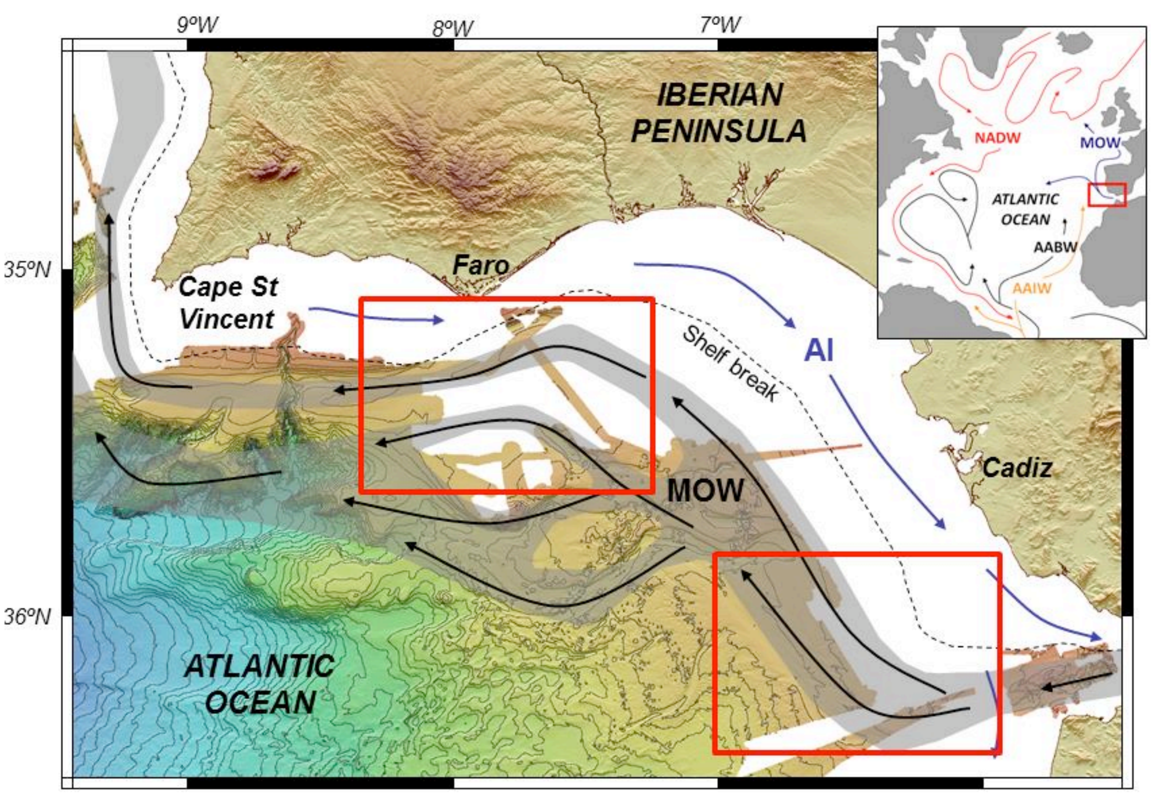


Figure 1.1: The Gulf of Cadiz and the main study area for this work (boxed). The main oceanographic components marked are the eastward-flowing Atlantic Inflow Waters (AI) and the Mediterranean Outflow Water (MOW). Modified from Hernández-Molina et al. (2003). Insert: The location of the Gulf of Cadiz (boxed in red) with respect to the principal thermohaline deep water masses in the Atlantic Ocean. AABW = Antarctic Bottom Water;

AAIW = Antarctic Intermediate Water; MOW = Mediterranean Outflow Water; NADW = North Atlantic Deep Water. Modified from Faugères et al. (1993).

The manuscript comprises of 10 chapters:

- **Chapter 2** will introduce the key body of literature covering contourites, and more specifically contourite sands and industry interest. This section will also give an overview of key concepts of contourite processes and products. The state-of-the-art understanding of the study area, located in the Gulf of Cadiz, is also introduced.
- In **Chapter 3**, the data-sets and methodology are outlined. A variety of data sources was used and this section covers both acoustic and sediment data. Methodology is described for multibeam and seismic analysis as well as the full sweep of sedimentary analysis carried out on sediment facies, composition, texture and dating.

A detailed account of work carried out on the Gulf of Cadiz contourite sands is outlined in two Results chapters as outlined below.

- **Chapter 4**: An examination of the acoustic data across the eastern Gulf of Cadiz, and a buried mixed system in the northern Gulf of Cadiz. This work aims to characterise contourite sands on a seismic scale, build upon sedimentological evidence for depositional processes, and examine the controls on contourite sand deposition.
- **Chapter 5**: The results of the sedimentary work are presented. **Section 5.1:** An analysis of the sedimentary facies and their sequences across the sand deposits aims to allow for a greater understanding of the spatial and temporal evolution of the system, and will move towards a new sandy contourite facies model. **Section 5.2:** A detailed compositional and **Section 5.3**: a textural analysis of the eastern Gulf of Cadiz characterises over 700 newly acquired sediment samples (surface and subsurface with the aim of aiding identification of sand-rich contourites in the geologic record elsewhere. **Section 5.4:** Newly acquired ^{14}C dates are presented to evaluate accumulation rates and aid core correlation.

All the evidence from the above work is compiled and discussed in four Interpretation and Discussion chapters.

- **Chapter 6**: The contourite features of the Gulf of Cadiz that have been identified in this study will be discussed. Two separate regions of the Gulf of Cadiz will be examined: 1) the present day and Quaternary evolution of the eastern Gulf of Cadiz, and 2) The evolution of the buried Pliocene contourite sand sheet and mixed system along the Algarve margin in the northern Gulf of Cadiz.

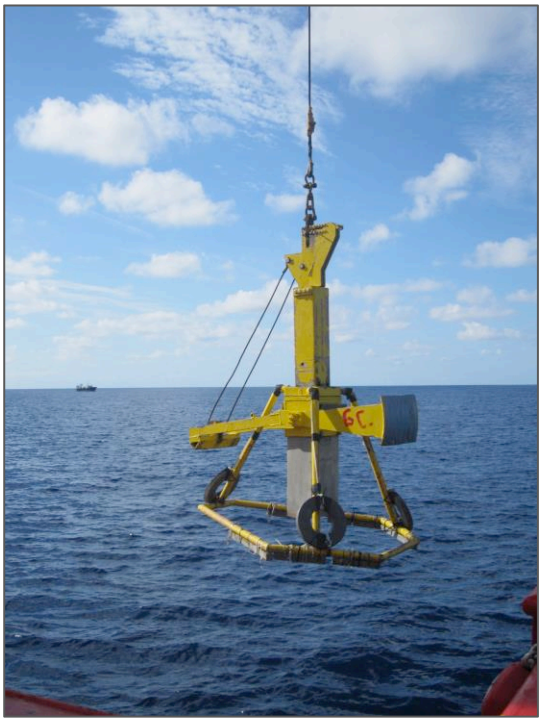
- **Chapter 7**: Here the results of the previous chapters are compiled and discussed with the aim of aiding contourite sand identification in the future. The facies and facies sequences identified will be examined and a new set of facies models for contourite sands proposed. Any characteristic trends within the sedimentological data that may aid to differentiate contourite sands from other deep water facies will also be noted.
- **Chapter 8:** The broader controls on contourite deposition are discussed and a new conceptual model for sequence stratigraphy outlined to aid prediction of further contourite sand deposits in the subsurface.
- **Chapter 9**: An examination of the economic potential of contourites with respect to petroleum reservoirs. A review of contourite sands and their related deposits is presented.
- Finally, in **Chapter 10**, key conclusions will be outlined and suggestions made on the future of contourite sand research, their economic importance and their key identification criteria. Recommendations for further work will also be made.

The results of this study are relevant, and contribute to the field by various means: 1) Firstly, the study presented is the first focused study of the eastern Gulf of Cadiz that utilises bathymetric, seismic *and* sedimentological data. Temporal and spatial changes to deposition across the study area highlight the complexity of a sand-rich contourite depositional system. This compliments work by other authors and collaborators on the wider Gulf of Cadiz region; 2) The acoustic character, sediment facies and sediment texture characterisation will aid future identification of these deposits along other continental margins and in the geological record; 3) A new model for sequence stratigraphy will aid prediction of further contourite sand deposits in the subsurface; and 4) A new state-of-the-art assessment of the economic potential of contourites (with a focus on contourite sand reservoir potential) will develop understanding of the geometries and internal architecture that are observed in sand-rich contourite deposits, with important applications for hydrocarbon exploration, reservoir modelling and production.

This data-set is perhaps the largest for any single sand-dominated contourite system acquired to date. Therefore in addition to improving our understanding of this depositional system, the study also develops our understanding of the mechanisms for contourite sand deposition on a global scale. Characterisation of these deposits will aid their identification in the subsurface and prove or disprove their reservoir and hydrocarbon play potential. Natural laboratories such as the Gulf of Cadiz provide ideal conditions for evaluation of these deposits and provide good quality end-member examples of sandy contourites in both ancient and modern examples.

From the work herein, two full academic papers have been published (Brackenridge et al. 2011; Brackenridge et al. 2012), (Appendix 1; 2) and another is being developed. Sections of the thesis have been used or adapted from parts of other papers as a contributing author Stow et al. 2012; Stow et al. 2013b), and contributed towards collaborative papers (Hernández-Molina et al. 2014; Llave et al. *In Press*). Furthermore, conference volume extended abstracts (Brackenridge et al. 2010; Brackenridge et al. 2012) and additional abstracts have been presented at conferences such as the International Association of Sedimentologists (IAS) Annual meeting, the American Association of Petroleum Geologists (AAPG) Annual Convention and the Congreso Geológico de España (Appendix 3). Finally, a contribution was made to IODP Proposal 644 in the form of a site survey appendix (Hernández-Molina et al. 2010a) and a workshop and field guide was written for the 'INQUA contourite core workshop for early career scientists' (Brackenridge et al. 2013a). All papers can be found in the Appendix section along with a documentation of all conferences, and courses attended throughout the PhD (Appendix 4).

Current Understanding & Research Aims



2 Current Understanding & Research Aims

2.1 Contourites and Contourite Sands

Contourites are found along many continental margins and form an important aspect of deep water sedimentation. In simplest terms, *"Contourites are all those sediments deposited by or significantly reworked by the persistent action of bottom currents"* (Stow et al. 2002b; Rebesco 2005; Rebesco and Camerlenghi 2008). Bottom currents can be formed by many processes, for example thermohaline, wind and internal wave processes in addition to benthic storms, overflows, interfaces between water masses, vertical eddies, horizontal vortices, tides and internal tides, internal waves and solitons, tsunami related traction currents and rogue or cyclonic waves (Shanmugam 2006; Shanmugam 2012b). Here we focus on contourites formed by thermohaline-driven geostrophic bottom currents in deep water. These are generated by the sinking of dense surface waters (thermohaline processes) and directed by gravity and Coriolis Forces. They generally follow the contours of the continental margin (orientated alongslope) and are able to erode the sea bed and deposit huge accumulations of sediment named 'drifts' (Fig. 2.1). They can also interact with other processes such as gravity driven turbiditic or mass-wasting processes (Hernández-Molina et al. 2008; Rebesco and Camerlenghi 2008).

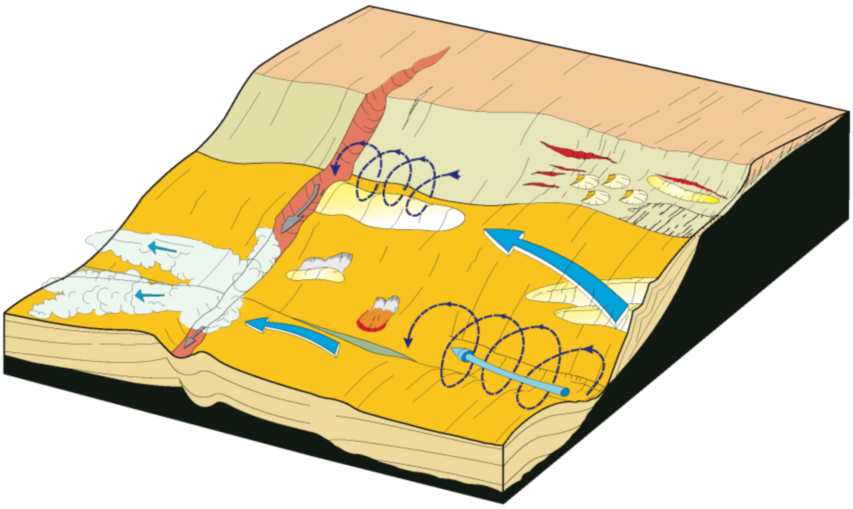


Figure 2.1: Bottom currents and their products. These currents generally follow the contours of the continental margin and can interact with other processes such as gravity driven turbiditic or mass-wasting systems. (Hernández-Molina et al. 2008; Rebesco and Camerlenghi 2008).

Contourite science has had a slow start when compared to research into other deep water processes and products, and as a result there is a relative lack of literature and ongoing research in the field. This is due primarily to the lack of industry interest when compared to turbidite deposition, and a lack of interest from research bodies from a geohazards point of view when compared to mass-wasting deposits. Even pelagic muds have long been more targeted for their uninterrupted record of past climate record, magnetic evidence for plate tectonics and their high organic content.

Since sediment transport by deep ocean currents was first discovered off the Eastern US margin by Heezen and Hollister (1963), contourite science has greatly benefited from multiple collaborative volumes and dedicated conferences over the last decades (Stow and Faugères 1998; Zhenzhong and Eriksson 1998; Stow et al. 2002b; Viana and Rebesco 2007; Rebesco and Camerlenghi 2008; Hernández-Molina et al. 2010b; Rogerson et al. 2013). A recent collaborative volume forms the most extensive accumulation of contourite knowledge (Rebesco and Camerlenghi 2008). Much progress has been made to characterise these generally mud-dominated deposits based on their seismic expression (Faugères et al. 1999; Llave et al. 2001; Rebesco and Stow 2001; Viana et al. 2001; Stow et al. 2002b; Hernández-Molina et al. 2008; Nielsen et al. 2008; Brackenridge et al. 2013b) and sediment facies (Gonthier et al. 1984; Stow et al. 1986; 1998; Faugères and Stow 1993; Shanmugam 2006; Stow and Faugères 2008). As a result, there is an ever-growing understanding of the processes that form these systems (McCave and Tucholke 1986; Faugères and Stow 1993; McCave 2008; Stow et al. 2008; Shanmugam 2012b). The Rebesco and Camerlenghi textbook (2008) highlights the growing importance of contourites from a palaeoceanographic (Knutz 2008), slope stability (Laberg and Camerlenghi 2008) and economic (Viana 2008) perspective. This has resulted in increasing interest from industry and academia alike, with two IODP cruises targeting contourite sediments in 2012 for palaeoclimatic study (Expedition 342 Scientist 2012; Hernández-Molina et al. 2013b; Stow et al. 2013a) and growing interest and examples coming from industry over the last five years (Stow et al. 2011a; Mutti and Carminatti 2012; Viana and Almeida Jr. 2012; Clare 2013). The most up to date account of contourite understanding is given by Rebesco et al. (2014).

When compared to fine-grained contourites, the occurrence of publications focusing on *contourite sands* is relatively rare and limited to only a few authors and study localities. By far the main body of literature on the subject has been documented by Shanmugam in text books (Shanmugam et al. 1995; Shanmugam 2006; 2012b). These books, primarily aimed at industry, focus on core and seismic examples from the Gulf of Mexico and consist of an abundance of core photographs showing bedforms, traction surfaces and mud drapes. Such features have also been observed elsewhere, for example in cases identified in Asia (Youbin et al. 2008; 2011) although their origin is still under dispute (Shanmugam 2012a). The evidence used to diagnose these sediments as contourite in origin is far removed from those observed in other contourite sand examples from the Atlantic Ocean as studied by Lovell and Stow (1981), Nelson et al. (1993), Viana et al, (1998), Akhmetzhanov et al. (2007), Moraes et al. (2007), Masson et al. (2010), and Stow et al. (2013b). In all these examples, contourite sands how much more limited bedform features and bioturbation is more common as is seen in mud-rich contourites (Rebesco 2005; Stow and Faugères 2008).

The discrepancies between the two bodies of literature is astonishing, and has led to heated debate, and at times personal attack in the literature. One reason for the differences may be due to the terminology used by the two bodies of literature to define contourites. Here, we use the Rebesco and Camerlenghi (2008) definition that is used by the vast majority of contourite scientists: that *"contourites are sediments deposited by or substantially reworked by the persistent action of bottom currents"* (Rebesco et al. 2014). Rebesco ans Camerlenghi (2008) emphasise that the definition encompasses many different types of bottom current and that the term contourite should be used as a generic name for a group of deposits, much like 'mass wasting deposits' covers debrites, slumps, and other downslope systems. Shanmugam (2012b) uses the term contourite to only describe those deposits influenced by contour currents (thermohaline-driven geostrophic currents). Additional terms are used for wind-driven and internal tide processes, and all are grouped under the term 'bottom current reworked sands' (Shanmugam 2006; 2012b; Mutti and Carminatti 2012). Other factors that will control the facies identified are poorly understood and will be discussed in this thesis.

Here, contourite sands are defined as those deposits that are so significantly reworked by deep bottom currents that little to no indication of downslope processes are evident. Since erosional elements are often also present, it is perhaps more accurate to name these *contourite depositional systems* (Hernández-Molina et al. 2008). Examples have been studied off the northwest European margin (Akhmetzhanov et al. 2007; Huvenne et al. 2009; Masson et al. 2010), offshore Brazil (Viana et al. 1998; Moraes et al. 2007; Bulhões et al. 2012; Mutti and Carminatti 2012) and, by far the most impressive and extensive example, in the Gulf of Cadiz in the east Atlantic (Nelson et al. 1993; Habgood et al. 2003; Hernández-Molina et al. 2006; 2014; Stow et al. 2011a; 2013b). There are principally two varieties of contourite sands found, largely depending on the available sediment supply at the locality. By definition, sand is those sediment grains greater than 63 µm in diameter and facies can be carbonate (calcarenite) or mixed siliciclastic-bioclastic (Zhengzhong and Eriksson 1998). A number of foraminifera sands have been interpreted as contourite deposits both along the northern margin of north Spain (Van Rooij et al. 2010; Alejo et al. 2012) and in the northeast Atlantic (Huvenne et al. 2009). These deposits are dominated by formanifera tests which require relatively low velocity bottom currents for distribution and deposition (velocities in the order of 2-3 cm s^{-1} has been recorded by Pingree and Le Cann (1990) along the northern Spanish margin). Other contourite sands are typically mixed siliciclastic-bioclastic in composition and require vigorous prolonged bottom currents to transport these larger grain sizes of higher bulk density. Arguably the best example of such a deposit has formed in the Gulf of Cadiz, where the Mediterranean Outflow Water is accelerated through the narrow Strait of Gibraltar (the Gibraltar Gateway) and into the Atlantic Ocean at velocities of up to 280 cm s^{-1} (Mulder et al. 2003). Consequently, an extensive and complex contourite depositional system has developed that broadly decreases in grain size with distance from the Strait in response to waning bottom current velocities (see Hernández-Molina et al. (2003; 2006) and references therein). Such deposits require some mechanism for enhancing bottom currents locally- usually through morphological forcing such as an oceanic gateway or erosional channel. Much work has been done on the contourite sands off the Brazilian margin that form depositional bedforms and channel deposits (Viana et al. 2001; Moraes et al. 2007; Bulhões et al. 2012; Mutti and Carminatti 2012) and the channel sand deposits on the northwest European contourite depositional systems (Akhmetzhanoz et al. 2007).

The data used in this study is gathered from the Gulf of Cadiz sand-rich contourite depositional system (CDS), located in the eastern Atlantic Ocean. A large CDS has developed across the entire southwest Iberian continental margin (Hernández-Molina et al. 2003; 2006) and is one of the most extensive and best studied in the world today. Contourite sedimentation is estimated to have begun in the early Pliocene (Llave et al. 2001; 2010; Brackenridge et al. 2012; Roque et al. 2012; Stow et al. 2013a). Hernández-Molina et al. (2003; 2003) has identified five distinct 'morphological sectors' that have developed in direct response to the broadly diminishing bottom current velocities from the proximal sector close to the Gibraltar Gateway in the east, to the canyons sector in the west where bottom current velocities are so reduced that downslope processes begin to dominate. These 'morphological sectors' have been used in published literature since. Research on this CDS historically began in sector 4: the 'depositional drifts sector', on account of the impressive large-scale mounded contourite drifts identified on seismic that was acquired in the 1980s (Faugères et al. 1984; Gonthier et al. 1984; Stow et al. 1986; Llave et al. 2001). Other authors have focused on the submarine canyons of sector 5 (Mulder et al. 2006; Marches et al. 2007; 2010) and the lower slope sediment lobes and waves of sector 2 (Habgood et al. 2003; Mulder et al. 2003; 2009; Hanquiez et al. 2010; Rogerson et al. 2012). Other studies examine the channels sector (sector 3) in the mid-Gulf of

Cadiz (Llave et al. 2007b; Garcia et al. 2009; Rogerson et al. 2011; Stow et al. 2013b), and are often focused on the neotectonics across that sector (Fernandez-Puga et al. 2007; Tasianas 2010).

Sector 1, the most proximal to the Gibraltar Gateway, has been comparatively less studied. Work has been carried out on the adjacent continental shelf (Nelson et al. 1999; Lobo et al. 2010), and the adjacent channel and sediment waves sectors, as well as across the Gibraltar Gateway (Kelling and Stanley 1972; Esteras et al. 2000), and the Mediterranean side of the Strait (Campillo et al. 1992; Ercilla et al. 2102; Juan et al. 2012). Focused studies on sector 1 however remained limited to a very few; two industry studies (Buitrago et al. 2001; Antich et al. 2005), some superficial and remotely-sensed studies (Kenyon and Belderson 1973; Mulder et al. 2003; Hanquiez et al. 2007), and some recent publications relating to the data used in this study (Alejo et al. 2012; Brackenridge et al. 2013d; Hernández-Molina et al. 2013a; 2014). The lack of focus on this area is for a number of reasons: 1) the draw of impressive large-scale features (mounded drifts) elsewhere in the Gulf of Cadiz which could be imaged relatively clearly with early seismic and other acoustic surveys when compared to the sand-dominated, high backscatter eastern sector; 2) The relative difficulty in sampling coarse unconsolidated sands under high velocity flow. Superficial sample efforts often fail due to difficult bottom current conditions, and other methods of drilling prove difficult due to borehole stability problems (Expedition 339 Scientists 2012); 3) High rates of erosion result in this area being of little interest to palaeoceanographers who seek complete records; and 4) It was not until recently that contourites have been considered for their economical (hydrocarbon reservoir) potential (Viana et al. 2007; Stow et al. 2011a) and therefore there was limited justification or need to investigate these sands.

2.2 The Gulf of Cadiz

2.2.1 Geological Setting

Many researchers have worked in the Gulf of Cadiz, which has had a complex geological history (Fig. 2.2). Studies of the pre-contourite history have been focused on the structural evolution of the region (Maldonado et al. 1999; Nelson and Maldonado 1999; Medialdea et al. 2004; Gutscher et al. 2009). Deep-penetrating seismic surveys have led to a greater understanding of the evolution of the continental plate margins in the eastern Atlantic Ocean (Srivastava et al. 1990; Roest and Srivastava 1991; Terrinha et al. 2009; Zitellini et al. 2009) and the reconstruction of the Cenezoic tectostratigraphy (Torelli et al. 1997; Lopes et al. 2006; Marches et al. 2010). Although the region is now relatively stable, this margin has had a complex and dynamic tectonic history as a result of its location on the transform zone between

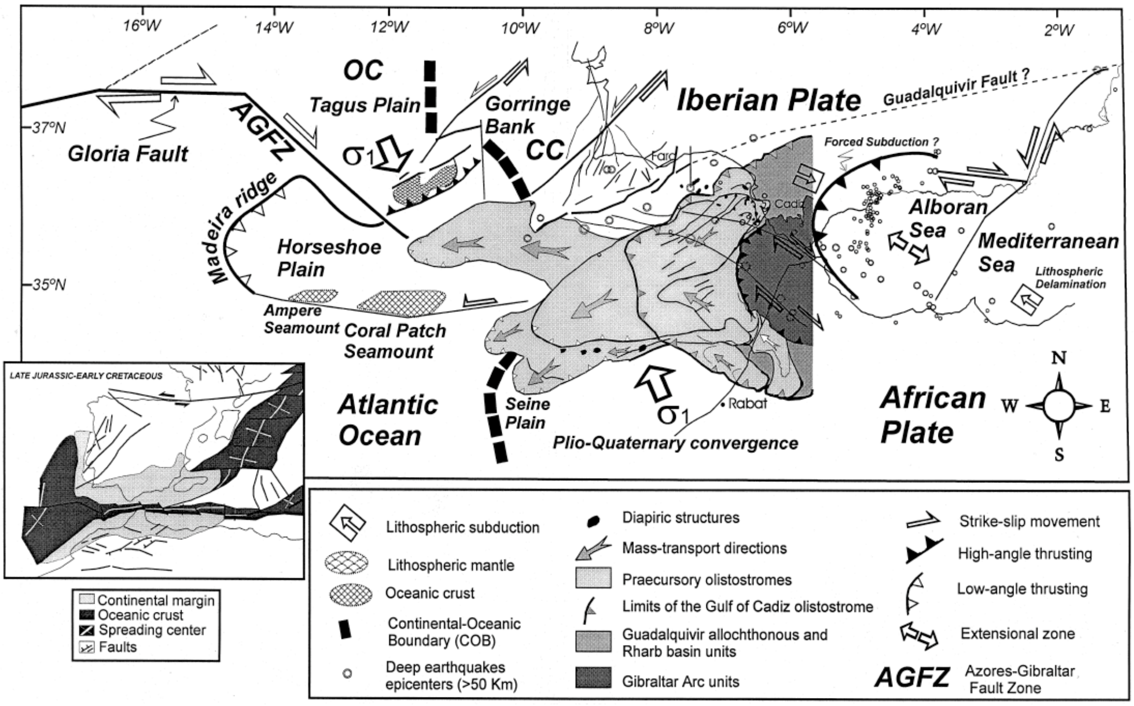


Figure 2.2: The structural framework of the Gulf of Cadiz. AGFZ = Azores-Gibraltar Fracture Zone; OC = Oceanic Crust; CC = Continental Crust. Insert presents a schematic of the Early-Cretaceous palaeotectonic set-up. Maldonado et al. (1999).

the African and Eurasian continental plates. Geophysical studies have aided the interpretation of the margin evolution (Maldonado and Nelson 1999b; Maldonado et al. 1999; Gutscher et al. 2002; Medialdea et al. 2004). The study area is bounded to the east by the Gibraltar Arc, which represents the westernmost limit of the Alps, and to the west by the complex Azores-Gibraltar Fracture Zone (AGFZ) (Fig. 2.2). The AGFZ becomes less distinct in the Gulf of Cadiz, and represents the diffuse boundary between the African and Eurasian continental plates which, although currently a convergent boundary, was in fact divergent from the Triassic to the Late Cretaceous (Fig. 2.3). The plate boundary between the African and Eurasian plates has periodically 'jumped' (Srivastava et al. 1990) and at times the Iberian plate acted independently of the Eurasian continental plate (Roest and Srivastava 1991).

As a result of this complex plate boundary history, an array of extensional, compressional and strike-slip tectonic structures can be observed along the margin (Fig. 2.2), many showing evidence of reactivation throughout geological history. Today, neotectonics play an important role along the margin. The placement of an unstable allocthonous unit in the Miocene has led to intense halokinesis along the margin which affects the modern day oceanic set-up and adds to the challenge when deciphering the depositional history of the margin. Three key events have been identified as crucial historical events responsible for the modern set-up of the margin (Fig. 2.3) (Maldonado et al. 1999; Hernández-Molina et al. 2006): 1) Late Mesozoic passive margin development related to rifting, sea floor spreading and the opening of the

Tethys and Atlantic Oceans; 2) Cenozoic convergence of the African and Eurasian plates in a N-S direction; and 3) foredeep formation relating to orogenesis to the east of the Gulf of Cadiz. These are discussed below.

2.2.1.1 *Mesozoic passive margin development*

Initial continental rifting of the super-continent Pangea saw extensional processes ongoing in the Gulf of Cadiz region from the Triassic to the Late Cretaceous. The splitting of Gondwana and subsequent sea floor spreading in the Triassic allowed for the formation of the Tethys Ocean and passive margin development in the Gulf of Cadiz region (Fig. 2.3 A). Separation of the African and Iberian margins continued throughout the Jurassic while rifting in the west began the spreading of the Atlantic Ocean. Expansion of the Atlantic Ocean led to the rotation of the Iberian Plate and the deformation of passive margin sediments in the Gulf of Cadiz. By

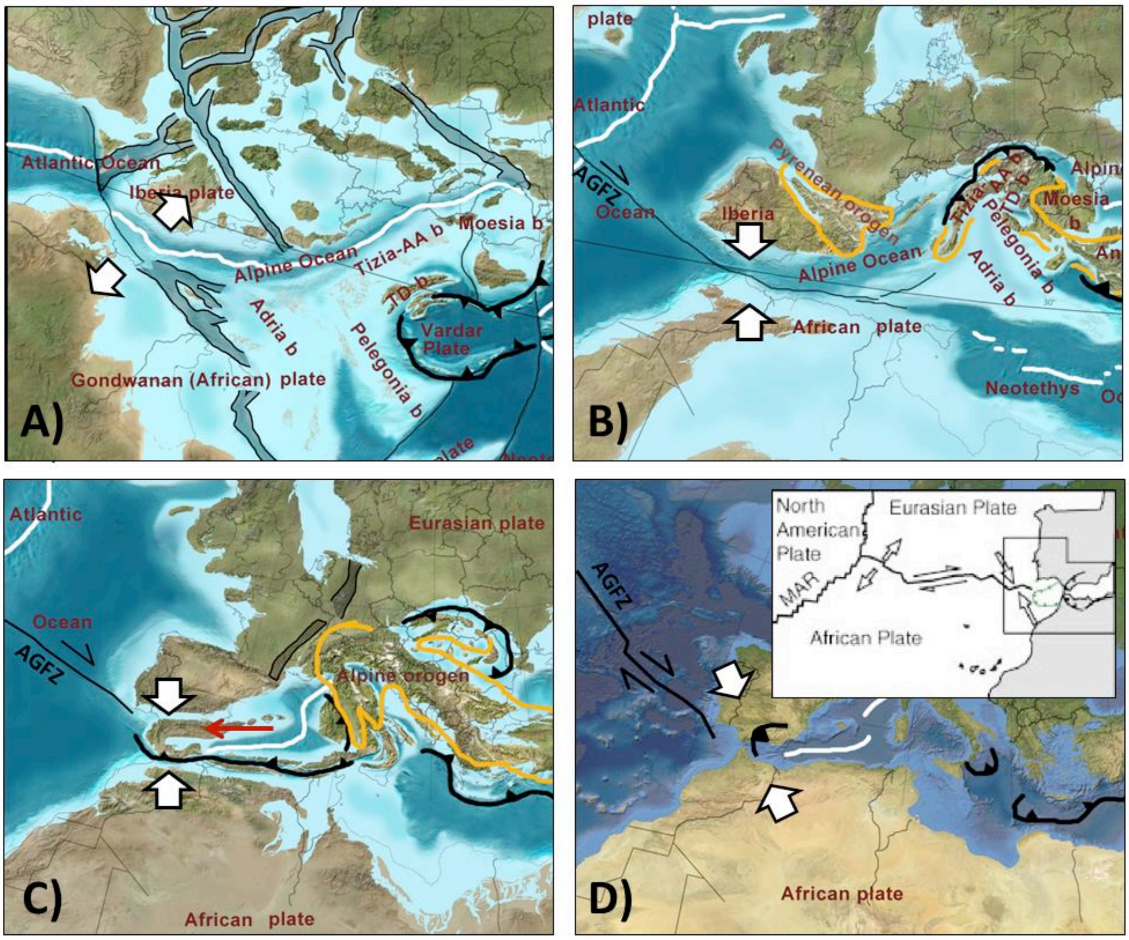


Figure 2.3: Evolution of the Gulf of Cadiz. A) Mesozoic (Late Cretaceous) passive margin development. B) Cenozoic (Late Eocene) convergence. C) Olig-Miocene foredeep formation and Allocthonous Unit placement. D) Present day margin set-up. *AGFZ = Azores-Gibraltar Fracture Zone. Insert presents a schematic of the palaeotectonic set-up. Palaeogeography maps modified from Blakey (2011). Insert from Maldonado et al. (1999).*

the Late Cretaceous, extension between the African and Iberian plates had halted, and a new spreading centre formed along the northern margin of the Iberian plate (Fig. 2.3 A). This was a quiet time in the tectonic history of the Gulf of Cadiz, which then lay attached to the African Plate (Srivastava et al. 1990).

2.2.1.2 Cenozoic convergence

Having been attached to the African continental plate throughout the Late Cretaceous and Early Cenozoic, the Iberian plate became detached and convergence along the southern Iberian plate boundary commenced (Fig. 2.3 B). Convergence was initially small, most likely absorbed in strike-slip movements along the AGFZ to the west (Fig. 2.2) with minor convergence in the Gulf of Cadiz region (Roest and Srivastava 1991). By the Oligocene, increased rates of shortening between the African and Iberian plate (now attached to the Eurasian plate) eventually led to the subduction of the Tethys oceanic crust under the African continental plate (Fig. 2.3 C). An estimated 200 km of N-S orientated shortening occurred during the Oligocene and Miocene (Maldonado et al. 1999). Associated tectonic movements also affected the region such as back-arc rifting and orogenesis.

2.2.1.3 Foredeep formation

Continued convergence of the African and Eurasian plates resulted in rollback and associated extensional rifting in the Western Mediterranean throughout the Oligo-Miocene. Compression led to pop-up structures and mountain building. In the Late Miocene, extensional collapse of the resulting Betic and Rif belts resulted in the movement of huge volumes of material westward over the Gulf of Cadiz (Fig. 2.3 C). This material formed an accretionary wedge named the 'Cadiz Allocthonous Unit' – a thick, unstable chaotic seismic unit that is continuing to migrate westwards due to ongoing tectonic compression and gravity gliding (Fig. 2.2) (Roberts 1970; Torelli et al. 1997; Flinch and Vail 1998; Maldonado et al. 1999; Medialdea et al. 2004; Hernández-Molina et al. 2006).

2.2.1.4 Modern day

Today, a compressional tectonic regime is ongoing in the Gulf of Cadiz although it is slowing and moving towards more stable conditions (Rosenbaum et al. 2002) (Fig. 2.3 D). The Eurasian and African plates are converging at a rate of approximately 4 mm/yr in a NE-SW direction (Maldonado et al. 1999). The AGFZ results in strike-slip tectonics to the west of the Gulf. To the East, mounting evidence points towards a region of forced lithospheric subduction of oceanic crust eastwards under the Alboran and Mediterranean Seas (Fig. 2.3 D) (Gutscher et al. 2002).

The resulting Gulf of Cadiz continental margin is convex, approximately 350 km long, and runs from the Strait of Gibraltar to the south-western tip of Portugal (Cape St Vincent). The margin comprises a shelf, upper and lower slopes and abyssal plains (Fig. 2.4). Note that a continental rise is absent from the margin. The shelf break is at a water depth of 120 – 140 m and the continental slope joins the abyssal plain at depths of over 4300 m. Features of the continental slope include depositional, erosional, neotectonic and fluid escape features (Hernández-Molina et al. 2006; Medialdea et al. 2009). Continued convergence between the African and Eurasian plates has led to intense deformation of the Cadiz Allocthonous Unit. Such a tectonically-active history has allowed for neotectonic activity in the form of salt and mud diapirs sourced from Triassic and Mid-Miocene marls and salts, which utilise existing faults and affect the modern sea floor throughout the Gulf forming diapiric ridges and adjacent depocentres (Somoza et al. 2003; Hernández-Molina et al. 2006; Llave et al. 2007b; Tasianas 2010).

2.2.2 Oceanographic Setting

The Gulf of Cadiz is dominated by the water exchange between the Atlantic Ocean and the Mediterranean Sea. The Strait of Gibraltar (from here-on the Gibraltar Gateway) allows for the exchange between the warm saline Mediterranean Outflow Water and the overlying Atlantic Inflow Water (Howe 1982; Baringer and Price 1999; Lobo et al. 2000; Ambar et al. 2002;

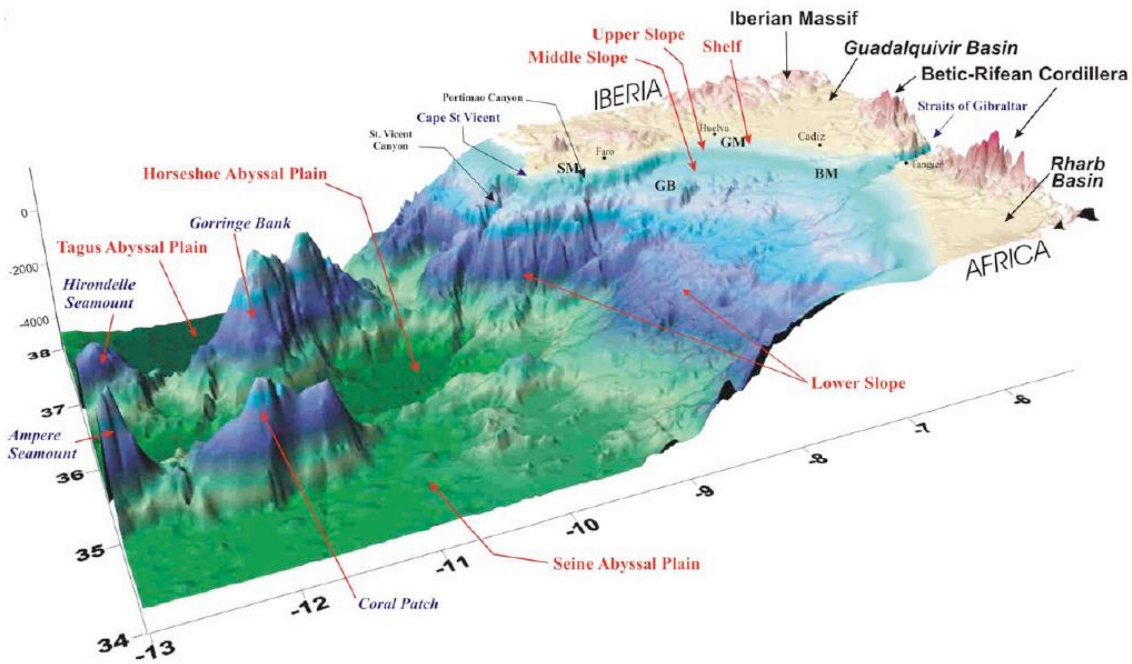


Figure 2.4: Regional bathymetry showing the modern day margin set-up of the Gulf of Cadiz. BM = Betic domain Margin; GB = Guadalquivir Bank; GM = Guadalquivir Margin (also known as the Algarve margin); SM = Sudibetic Margin. From Hernández-Molina et al. (2006).

Cabecadas et al. 2002; Garcia-Lafuente et al. 2006; Llave et al. 2007b). Much physical oceanographic research has been carried out on the Mediterranean Outflow Water (MOW) in recent decades and its modern day properties and route are now well constrained (Hernández-Molina et al. 2006). The MOW is composed of a mixture of two water masses sourced from the Mediterranean Basin: the Levantine Intermediate Water and a small component of the Western Mediterranean Deep Water (Millot 2009). This constricted basin with arid climate provides conditions for the formation of warm, saline dense water of 13˚C, 36.5 ‰ (Ambar and Howe 1979) at a number of 'bottom water kitchens' around the Mediterranean Basin. The Western Mediterranean Deep Water is formed in the Gulf of Lion, and fills the Basin below 500 m water depth, flowing around the Iberian Peninsula and Balearic Islands before exiting via the Alboran Sea in the westernmost Mediterranean through the Gibraltar Gateway. The Levantine Intermediate Water forms in the eastern Mediterranean Basin and flows at depths of 150-500 m over the upper- to mid- continental slopes, through the Sicilian Strait towards the Alboran Sea and Gibraltar Gateway (Millot 1999; 2009; Candela 2001). The water mass accelerates through the narrow Gibraltar Gateway – locally reaching velocities of up to 300 cm s^{-1} (Ambar and Howe 1979; Mulder et al. 2003) as it cascades over the shallow Camarinal Sill, located within the Gibraltar Gateway. It forms a turbulent gravity-driven flow before moving northwestwards along the mid-continental slope of the Gulf of Cadiz (Fig. 2.5). Density-driven descent (Legg et al. 2009) and mixing with overlying Atlantic Waters results in decreasing salinity along the margin from SE to NW (Baringer and Price 1997). Eventually the MOW leaves the sea bed and reaches a neutral buoyancy at a depth of 1400 m offshore the Cape St Vincent, where it begins to raft above the North Atlantic Deep Water (Zenk 1975; Ambar et al. 1999).

The MOW is restricted to a core approximately 10 km wide as it accelerates through the Gibraltar Gateway. Along the continental slope of the Gulf of Cadiz however, the MOW can exceed 80 km in width forming a broad tabular water mass (Baringer and Price 1997). Two distinct bottom current cores form, and split into branches contained within erosive channels. Late Cenozoic neotectonics have created diapiric ridges obliquely to the MOW flow direction. These ridges have undoubtedly been responsible for the splitting of the MOW into numerous distinctive cores (Fig. 2.5), although density-driven layering within the water mass has also been proposed as a contributing factor. Principal water cores are: a main Mediterranean Upper Water core, and a Mediterranean Lower Core that further subdivides into an Intermediate branch, Principal branch and Southern Branch (Llave et al. 2007b) (Fig. 2.5). Each branch demonstrates unique physical properties, such as salinity, temperature and average velocity (Zenk 1970; Ambar and Howe 1979; Ambar et al. 2002; Borenas et al. 2002). Overall,

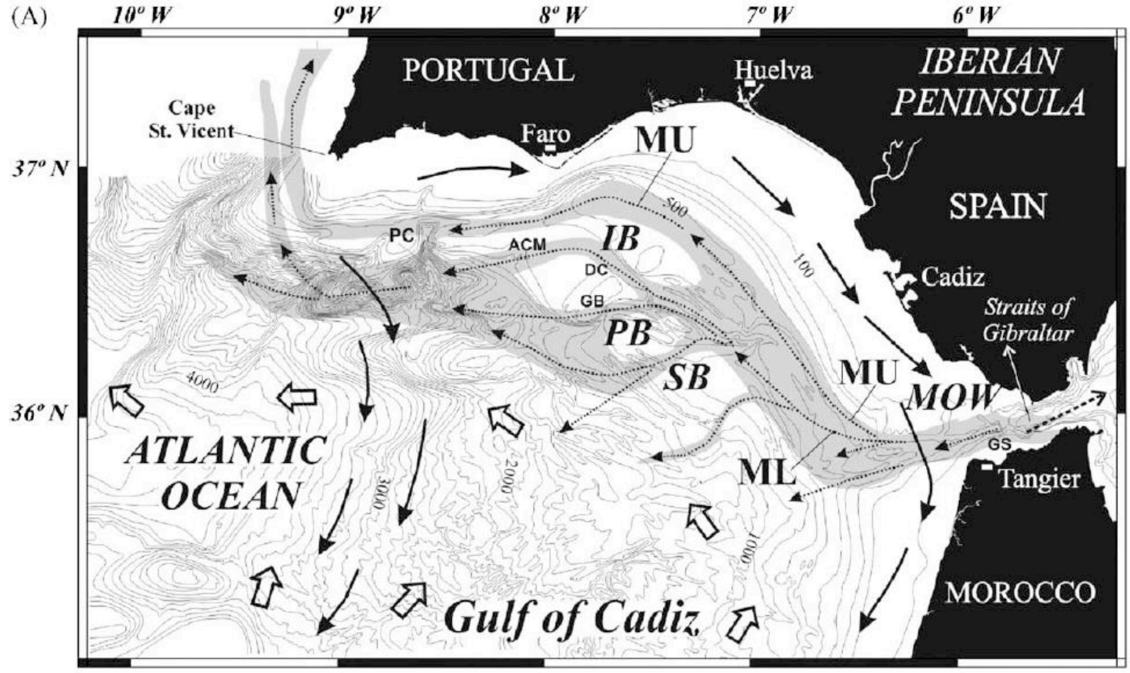


Figure 2.5: The present day morphology and the oceanographic set up of the Gulf of Cadiz. The Mediterranean Outflow Water (MOW) splits into numerous distinct branches due to the sea floor morphology and water density properties. From (Hernández-Molina et al. 2006).

the Upper Core is a smaller, warmer, less saline water mass when compared to the highly saline Lower Core which averages 20-30 cm s^{-1} (Llave et al. 2007b).

The movement of water masses through the Gibraltar Gateway was first recorded in the early 1900s (Nielsen 1912) and since then, numerous studies have shown that physical properties have remained fairly constant. There is more controversy surrounding the palaeo-evolution of the MOW. Data from the Mediterranean Basin shows that the Messinian Salinity Crisis ended in the latest Miocene (Bache et al. 2012). This signifies that the Gibraltar Gateway opened at this time so that the exchange of water was possible between the Atlantic Ocean and the Mediterranean Sea. The date of the initiation of the MOW is in dispute, but it is generally accepted that bottom water formation in the Mediterranean initiated sometime after the influx of the Atlantic water into the basin, probably in the Early to Mid-Pliocene (Hsü et al. 1973; Blanc et al. 2002; Llave et al. 2011; Bache et al. 2012). Since that time, variations in the MOW are clear from proxy data and the high cyclicity observed in acoustic data. Key observations are: 1) Several authors have demonstrate a more vigorous lower branch of the MOW during glacial times (Cacho et al. 2000; Hernández-Molina et al. 2003; 2006; Llave et al.

2006); 2) This is backed up by other work that points to a more vigorous upper branch of the MOW during the recent highstand period (Stow et al. 2002a; Brackenridge et al. 2011); 3) New work suggests that the outflow waters are highly dynamic and move up and downslope on numerous timescales. This is linked to changing relative densities between the Atlantic and the Mediterranean Waters and is driven by climatic fluctuations (Rogerson et al. 2005; 2012).

2.2.3 Contourite Depositional System

The MOW has swept the Gulf of Cadiz continental slope for *ca.* 4.5 Ma, and over this time it has directly affected the sediments deposited there. Sufficient velocities have been maintained to form contourites along the entire length of the margin from the Gibraltar Gateway to the Cape St Vincent (Fig. 2.6). The continental slope morphology is complex and consists of both depositional and erosional products. It is therefore practical to refer to the Gulf of Cadiz contourites as a contourite depositional *system* (Hernández-Molina et al. 2003). A contourite depositional system (CDS) will form along any continental margin where alongslope processes dominate over mass wasting, turbidity currents and pelagic settling processes (Hernández-Molina et al. 2008). Each depositional system will begin with some mechanism for enhancing bottom current velocity and will terminate where the transport capacity of the bottom current is diminished to such an extent that it is no longer capable of dominating over other depositional processes. A contourite depositional system will evolve over time and space, controlled by palaeoclimatic and oceanographic changes in addition to local tectonic activity that can affect the margin and water masses such as oceanic gateways and halokinesis (Viana et al. 2007).

The Gulf of Cadiz contourite depositional system (Fig. 2.6) initiates where the MOW overspills into the Atlantic Ocean as a highly saline dense water mass and is accelerated through the narrow conduit which connects the two oceans: the Gibraltar Gateway (Howe 1982). Features in the eastern Gulf of Cadiz are closely tied to the erosive capacity of the bottom water mass (i.e. its velocity) and the local sea bed morphology (Hernández-Molina et al. 2006) with laterally extensive abraded surfaces in the east moving to discrete contourite channels where outcropping diapiric structures manipulate the bottom water core. Contourite moats occur in the north of the Gulf of Cadiz and are associated with large-scale depositional features. A variety of contourite modern and buried drift types are observed along the margin, namely elongate mounded, sheeted, plastered and fan drifts. There is also a broad trend of decreasing mean grain size along the margin as the transport capacity of the MOW decreases with distance from the Gibraltar Gateway. Detailed investigations of the system has exposed five distinct 'morphosedimentary sectors' (Habgood et al. 2003; 2006; Hernández-Molina et al.

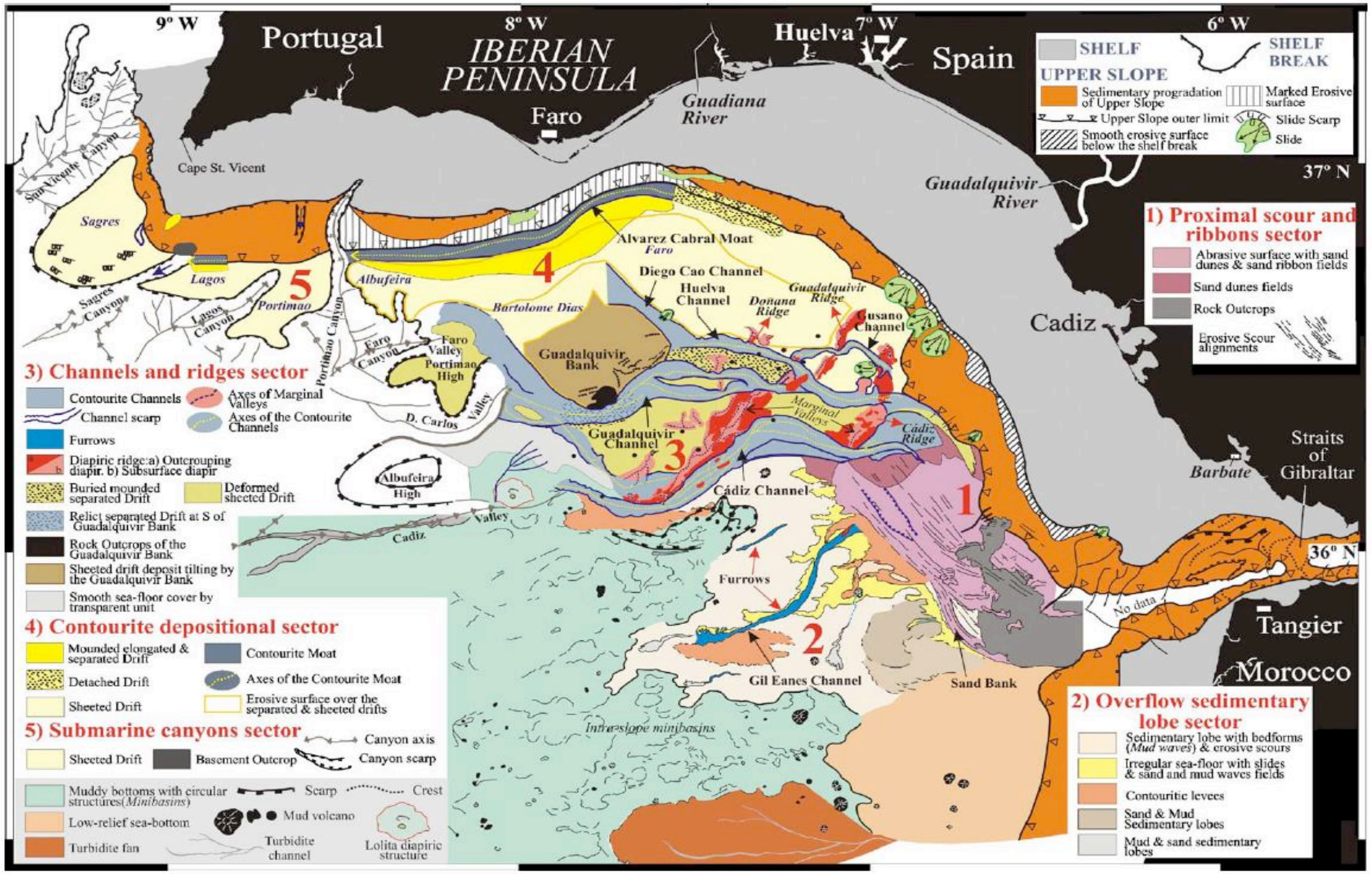


Figure 2.6 (overleaf): The morphosedimentary sectors as laid out by Hernández-Molina et al. (2006). This study focuses mainly on the contourite sands in sector one with some examples from other sectors.

2003; 2007b; Llave et al. 2001) each showing different characteristics and depositional/erosional features. They are named as: 1) Proximal scour and sand ribbons sector; 2) Overflow-sedimentary lobe sector; 3) Channels and ridges sector; 4) Active contourite drift sector; 5) Submarine canyons sector (Fig. 2.6). The morphosedimentary characteristics of each sector are determined by numerous interlinking factors including the deceleration of the MOW as it flows westwards and its interaction with the sea floor (Hernández-Molina et al. 2006). The principal characteristics of each sector are outlined herein.

2.2.3.1 Sector 1; proximal scour and ribbons sector

The 'proximal scour and ribbons sector' is one of the main focus areas of this research and was first identified and described by Kenyon and Belderson (1973). Since that study, bathymetric imaging, side-scan sonar, bottom photographs and sediment sampling has aided characterising this region (Habgood et al. 2003; Mulder et al. 2003; Hanquiez et al. 2007). This sector consists of high energy bottom current and gravity-driven overflow features. Proximal to the Gibraltar Gateway, the turbulent, gravity driven cascade of the MOW over the Camarinal Sill (Legg et al. 2009) has resulted in two deep erosional channels and outcrop features dominating (Hernández-Molina et al. 2014). Most recently, a new data acquisition campaign (see Chapter 3) has identified additional depositional drift features. Plastered drifts are seen along the upper slope, and two mounded drifts across two broad erosional terraces (Fig. 2.7) (Hernández-Molina et al. 2014). The two terraces (over 2000 km^2 in area) form a major abraded surface between 500 and 800 metres water depth (Fig. 2.7) (Hernández-Molina et al. 2014). This surface is dominated by erosional processes: seismic reflections show truncation and aligned features that are V-shaped in cross section, interpreted as erosive scours or giant furrows (Hernández-Molina et al. 2006). Most proximal to the Gibraltar Gateway, rock outcrops on the sea bed, and the region is characterised by high backscatter in side-scan sonar data indicating coarse grained sediments (Mulder et al. 2003). All these features suggest a highly vigorous current regime along the route of the MOW proximal to the Gibraltar Gateway. There are, however, some depositional features in this sector, suggesting a reduction in MOW velocity (and thus sediment transport capacity) moving away from the Gibraltar Gateway to the NW and laterally from the MOW core to the east and west (Mulder et al. 2003). Gravel and sand lag deposits give way to sand ribbon and wave deposits. Sand waves are seen on various scales and can be straight or interfering (Hanquiez et al. 2007). Orientations of all features follow the route of the MOW alongslope as it leaves the Gibraltar Gateway westward and then bends northwards due to Coriolis Forces.

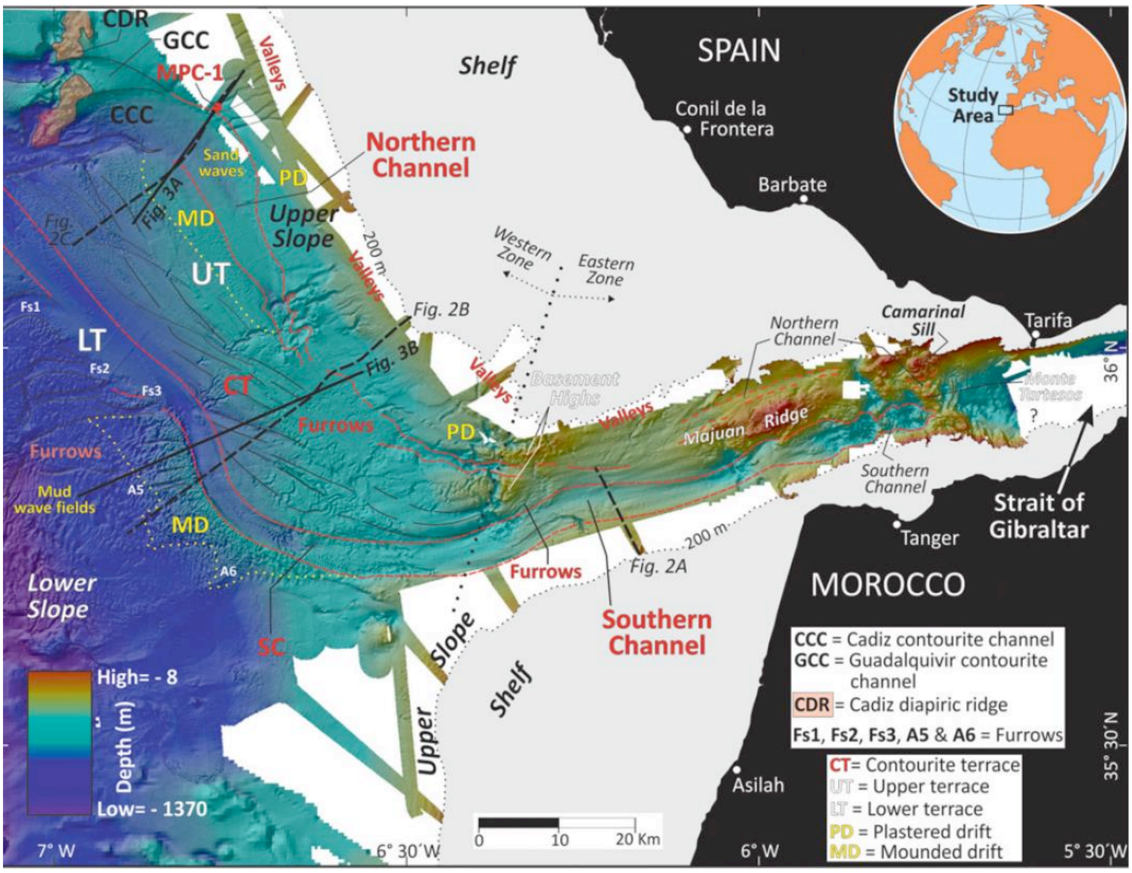


Figure 2.7: Bathymetry in Sector 1; the proximal scours and ribbons sector. Main depositional and erosional features indicated. From Hernández-Molina et al. (2014).

2.2.3.2 Sector 2; overflow-sedimentary lobe sector

Located downslope and seaward of Sector 1, this sector is also of interest in this study on account of its sand-rich contourite deposits. Located between 800 and 1600 metres water depth, this sector shows impressive sedimentary wave fields, downslope orientated channel and furrow erosive structures and associated depositional lobes (Hernández-Molina et al. 2006) (Fig. 2.6).

The largest depositional feature in this sector is a large contouritic drift that borders with the 'proximal scour and ribbons sector'. There has been some confusion as to the origin of this accumulation, with authors naming it a sand bank (Kenyon and Belderson 1973), sand ridge (Habgood et al. 2003), contouritic levee (Mulder et al. 2003; Hanquiez et al. 2007), and most recently, a contourite drift (Brackenridge et al. 2013b; 2013c). This large contourite accumulation is topped by an extensive sediment wave field (Habgood et al. 2003) that tends to be sandy in the north of this sector (Nelson et al. 1993), becoming muddier to the south and with increased water depth (Kenyon and Belderson 1973; Habgood et al. 2003).

Incising into these sediment wave fields are a series of downslope-orientated channels and furrows. Some, particularly the minor channels, have some oblique orientation. The largest of these channels is the Gil Eanes Channel (Fig. 2.6), which extends for 40 km down to 1200 m water depth (Habdood et al. 2003). The Gil Eanes Channel and the two other major channels in this sector are broadly u-shaped in cross section, contain bioclastic sands in their axes, and have sediment lobe complexes at their terminus. The origin of these lobe deposits has been debated, and the current understanding is climatic-driven periodic deepening of the MOW has led to incision (Rogerson et al. 2012), and induced gravity processes in this sector (Hanquiez et al. 2010). The lobes are therefore thought to be both of contouritic and turbiditic in origin.

Further features of note in this sector are mud volcanoes, which form topographic highs on the sea bed that can deflect channels (Somoza et al. 2003; Hanquiez et al. 2010). They also have important roles as conduits for gas migration and escape (Diaz-del-Rio et al. 2003; Fernandez-Puga et al. 2007).

2.2.3.3 Sector 3; channel and ridges sector

In this sector, diapiric ridges orientated perpendicular to MOW flow (Somoza et al. 2003; Fernandez-Puga et al. 2007; Medialdea et al. 2009; Tasianas 2010) and other tectonic basement highs (Vegas et al. 2004; Roque 2007) form morphologic obstructions and create distinct channels through which the MOW generates two cores: the Mediterranean upper and lower waters (Llave et al. *In Press*) (Fig. 2.5; 2.6). The result is a morphologically-forced acceleration of the branches of the MOW, leading to a higher erosional capacity and the formation of channels in this sector. They were first described by Nelson et al. (1993) and studies in this sector are continuing today (Baraza et al. 1999; Nelson et al. 1999; Habgood et al. 2003; Mulder et al. 2003; Llave et al. 2007a; Garcia et al. 2009; Stow et al. 2013b). Five major channels, and 4 minor channels have been described by Garcia et al. (2009) (Fig. 2.6). The major channels are named from the upper continental slope seaward; the Gusano, Huelva, Diego Cao, Guadalquivir and Cadiz channels and reach lengths of over 100 km (Hernández-Molina et al. 2006). Unlike the channels and furrows identified in Sector 2, these contourite channels tend to be sinuous and asymmetrical in cross section (Stow et al. 2013b).

These channels incise into upper slope sheeted drifts and mid-slope deformed sheeted and buried mounded drifts (Hernández-Molina et al. 2006; Llave et al. 2007a). This indicates a relatively recent development relating to a local enhancement of the MOW due to the growth of the diapiric ridges in the east of this sector. Buried mounded drifts indicate a change in the hydrodynamic set-up of this sector in the mid-Pleistocene (Llave et al. 2007a).

The deepest channel, the Cadiz channel, has been extensively characterised by Stow et al. (2013b), and along with sediment analysis of other channels it is clear that sand and gravel-rich deposits are associated with contourite channels (Nelson et al. 1993). They are therefore of great interest in this research.

2.2.3.4 Sector 4; active contourite drift sector

First recognised in the early 1980s, contourite drifts make up this overall depositional domain (Mougenot and Vanney 1982; Faugères et al. 1984; Gonthier et al. 1984; Stow et al. 1986). High sediment thicknesses mean that this sector shows the most complete record of the Mediterranean Outflow. As a result, much research has continued in this sector (Llave et al. 2001; 2011; 2010; Roque et al. 2002a; 2012; Lopes et al. 2006; Brackenridge et al. 2013b; Stow et al. 2013a).

The Faro-Albufeira elongate mounded drifts form the most seismically spectacular feature in the sector, with the associated erosive Alvarez-Cabal contourite moat separating them from the continental shelf and funnelling the MOW westwards (Fig. 2.6; 2.8). Named elongate-mounded using the Faugères et al. (1999) drift classification scheme based on their external morphology, these drifts show impressive upslope progradation patterns and laterally-extensive erosional discontinuities that can be linked to fluctuations in the intensity of the MOW. Such fluctuations are thought to be related to global climatic conditions, local neotectonics, and long-term geological 'pulsing' (Llave et al. 2001; Stow et al. 2011b). Downslope, and associated with the Faro-Albufeira elongate mounded drifts are a set of aggradational sheeted contourite drifts; the Faro-Cadiz, the Bartolomeu Dias and the Albufeira drifts (Hernández-Molina et al. 2006; Llave et al. 2011; Roque et al. 2012).

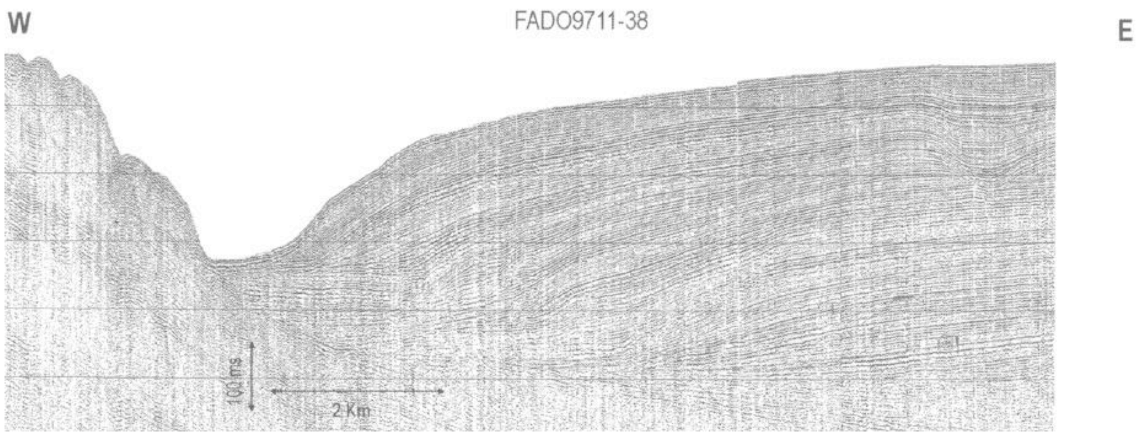


Figure 2.8: The Faro-Albufeira elongate mounded drift, and associated contourite moat. Located in sector 4, the 'active contourite drift sector'. From Llave et al. (2007a).

The drifts in this sector have formed much of the base work for the creation of the contourite facies model (Gonthier et al. 1984; Stow et al. 1986; Stow and Faugères 2008). Although the bulk of the contourite sediments are mud-dominated, discrete thin sandy layers have been identified throughout (Hernández-Molina et al. 2013c; Stow et al. 2013a). Prior to elongate-mounded drift development in the Quaternary (Llave et al. 2011), multiple processes were ongoing with mass wasting, turbiditic and contouritic mixed deposition throughout the Pliocene (Brackenridge et al. 2013b; Stow et al. 2013a).

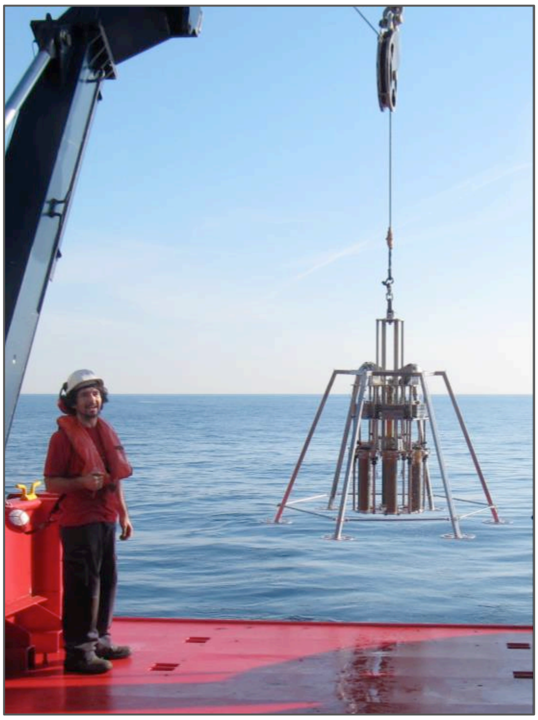
2.2.3.5 Sector 5; submarine canyons sector

The westernmost of the Gulf of Cadiz sectors, the 'submarine canyons sector' is largely dominated by downslope erosive features and muddy plastered and sheeted contourite drifts (Hernández-Molina et al. 2006; Roque et al. 2012). Although this sector contains no substantial sand-rich contourite deposits, it demonstrates the interaction between downslope and alongslope processes well (Marches et al. 2007; 2010). The largest feature of the sector is the Portimao Canyon orientated downslope (NE-SW), with the smaller Lagos, Sagres and San Vincente canyons also forming significant features on the sea bed (Fig. 2.6). These canyons are surrounded by contourite deposits, named the Lagos, Portimao and Sagres sheeted drifts and the minor Lagos elongate mounded drift (Llave et al. 2001). Interbedded with these muddy contouritic sediments are sand-rich downslope deposits, believed to have been deposited during times of relative sea-level lows when the sediment influx from the continental shelf was much higher (Marches et al. 2010).

This sector differs greatly from the adjacent 'active contourite drift sector' on account of the capture of the MOW as it passes over the Portimao Canyon (Marches et al. 2007). This is evidenced as a change in depositional drift type, a significant reduction in bottom current velocity, and a decrease in average grain size across the canyon (Mulder et al. 2006; Marches et al. 2007). This has important implications for the controls on contourite sand deposition and downslope/alongslope process interaction.

The Gulf of Cadiz contourite depositional system ends where the MOW leaves the sea bed to the southwest of the Cape St Vincent. The MOW turns north and follows the western Iberian continental margin. There is some evidence for local present day interaction with the western Portuguese margin (Alves et al. 2003), and when it reaches the northwest Iberian Margin. Here, the MOW is present on the sea floor (Fiúza et al. 1998) and has formed several contourite depositional systems along the Galician and Cantabrian continental margins (Ercilla et al. 2010; Mena et al. 2010; Van Rooij et al. 2010; Hernández-Molina et al. 2011a; Alejo et al. 2012; Bender et al. 2012).

Data & Methodology



3 Data & Methodology

3.1 Data-Sets

This study utilises various types of data and of differing vintages (Fig. 3.1; Table 3.1). The majority of the data used to characterise the eastern Gulf of Cadiz sands was collected aboard the Scientific Cruise CONTOURIBER-1 which sailed in October 2010 on the Spanish CSIC vessel the RV Sarmiento de Gamboa. Additional data from other sectors of the Gulf of Cadiz are of different vintages as outlined below.

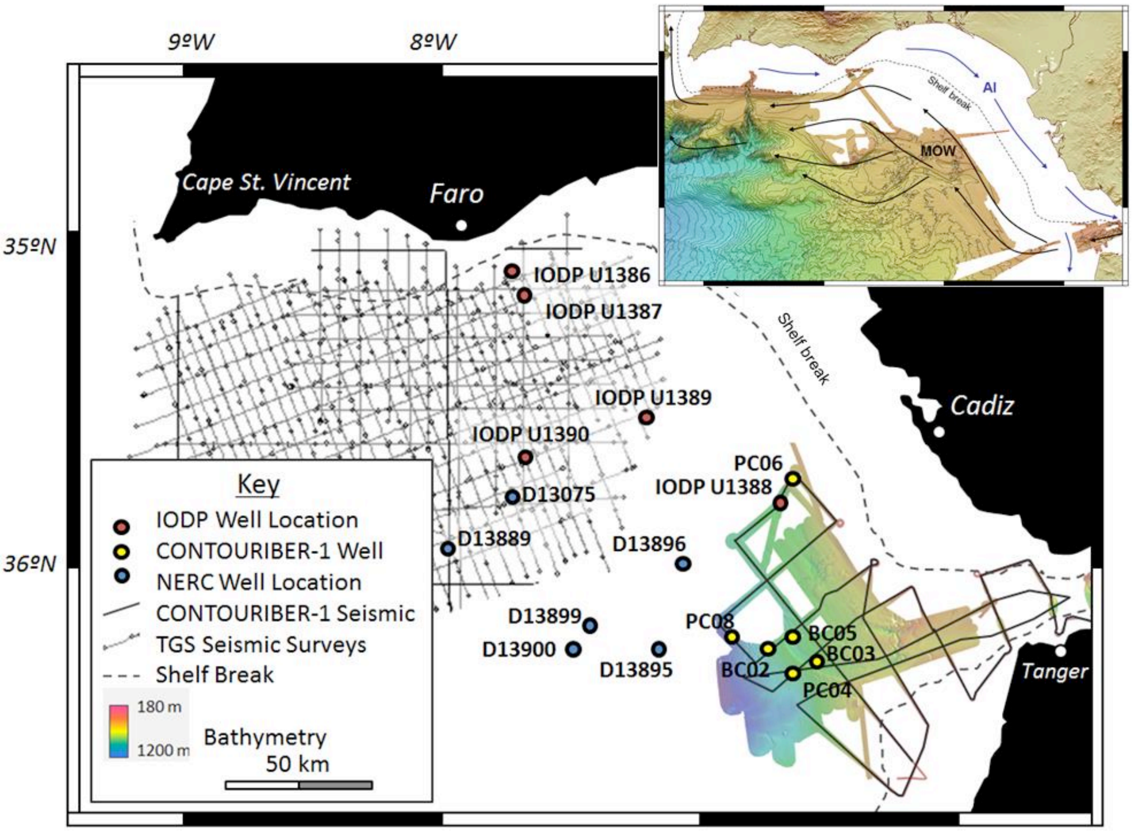


Figure 3.1: Compilation of the data used in thesis research. Two seismic surveys have been used with a parasound data-set in the easternmost Gulf of Cadiz. In addition, a newly acquired set of gravity cores was collected in the easternmost sector (BC05, PC04, PC06, PC08), five IODP cores (U1386, U1387, U1388, U1389, U1390) and four historic cores (D13686, D13896, D13898, D13900) now stored at BOSCORF.

Data Type	Data-set	Quantity	Size (used in this study)
Bathymetry	Multibeam bathymetry	1	~ 13,000 km^2
Acoustic	CONTOURIBER 2D seismic	27	780 km
	TOPAS Parasound	43	~ 900 km
	TGS 2D seismic survey PD00	95	15,000 km
	TGS 2D seismic survey PR00		
Sediment Core	CONTOURIBER Box Core	1	0.23 m
	CONTOURIBER Piston Core	3	14 m
	NERC Piston Core	6	25 m
	IODP Conventional Core	3	26 m
Grain size Data	CONTOURIBER sample	791	n/a
Dating	^{14}C Dating	15	n/a

Table 3.1: List of data used in this study.

3.1.1 Acoustic Data

New 2D seismic, parasound, and bathymetric data-sets were collected across the easternmost Gulf of Cadiz. All these remote sensing data-sets were collected on the Scientific Cruise CONTOURIBER-1 which sailed in October 2010. A total of ~780 km of seismic and parasound was acquired to form the main tie between core data and depositional environment in the Quaternary. The bathymetric data gives a good impression of the modern day morphology of the margin.

The *2D seismic data-set,* consisting of 27 lines (Fig. 3.1), was acquired using a single-channel mini-streamer targeting the shallow (up to approx. 2 km) sediment. A sleevegun and hydrophone array was towed behind the vessel and the ~780 km of seismic data was prepared by geophysicists on-board the vessel. Key transects were recorded to complement the accompanying bathymetric survey and loaded into the seismic software Petrel 2.7 for analysis. The final seismic sections are of moderate quality with varying signal:noise based on the water wave conditions at the time of acquisition. Penetration is on the order of 2 ms with a noted reduction in quality below 1.5 ms TWT. An accompanying *parasound data-set* complements the core data in the region (Fig. 3.2). Parasound differs from seismic data due to the frequency of the energy source used. The high frequency acoustic source allows for the top metres of the subsurface to be imaged with high vertical and horizontal resolution (Grant and Schreiber 1990). This allows for it to be integrated with piston core data to make conclusions on the lateral organisation of the sediments in the study. Finally, a new *bathymetric data-set* was gathered using a deep water Multibeam Echosounder (Fig. 3.2). It extends and complements

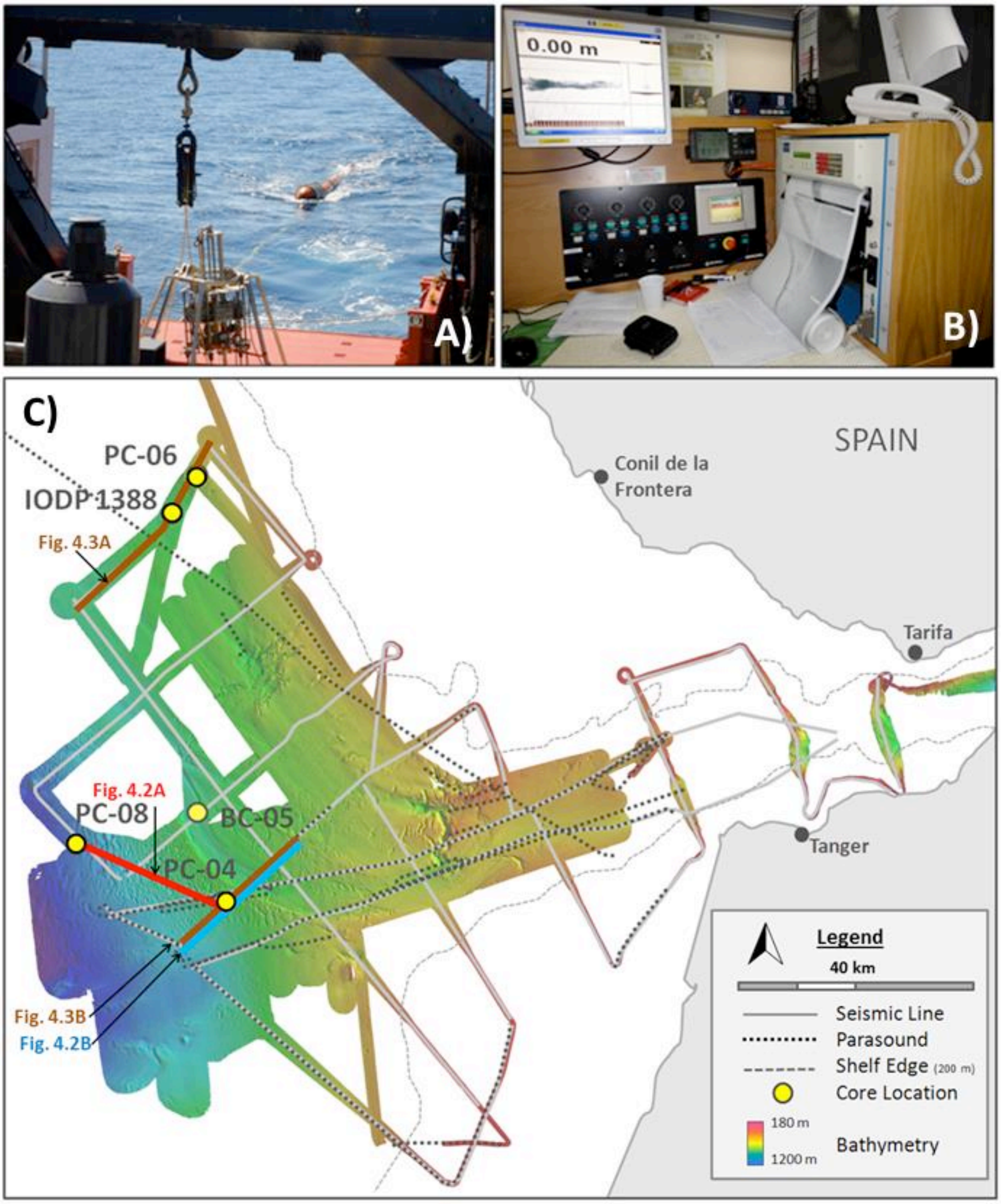


Figure 3.2: Data-set collected during the Scientific Cruise CONTOURIBER-1 October 2013: A) 2D single- channel seismic airgun; B) Parasound data collection; C) Acoustic data-set including the bathymetric and seismic data. Key core locations also marked.

the previously compiled Gulf of Cadiz bathymetric dataset (SWIM Map Team 2007; Zitellini et al. 2009) (Fig. 3.1 insert). The bathymetric data was collected using a Multibeam Echosounder operating at 14.5 – 16 kHz (CSIC Unidad de Tecnologia Marina).

To the west of the Gulf of Cadiz (sector 4), an additional seismic survey was used to examine the controls on contourite deposition in a Pliocene mixed system (Brackenridge et al. 2013b) (Fig. 3.1). When compared to the seismic data in the east of the Gulf of Cadiz, the penetration depth is much deeper and of lower resolution than the seismic survey in the east of the study area, and the entire Neogene section can be clearly imaged. The data comprised two surveys (Fig. 3.3). Survey PD00 was acquired by TGS-NOPEC in 2000 using a tuned bolt array with a shot point interval of 12.5m (TGS 2005). Survey PR00 was acquired at an earlier date, but reprocessed in 2000 with survey PD00 (George 2011). A total of 95 lines in the mid- to western- portion of the Gulf of Cadiz make up the data-set, between 160 and 320 km WNW of the Gibraltar Gateway. The lines cover part of the continental shelf and extend downslope to water depths of up to 3000 m. The 2D seismic grid is relatively dense with offsets of 5-10 km between lines that range from 140 to 300 km in length. Additional data over the area includes a detailed bathymetric map and marine gravity (TGS 2005; Zitellini et al. 2009). The interpretation was completed in the software SMT Kingdom 8.5.

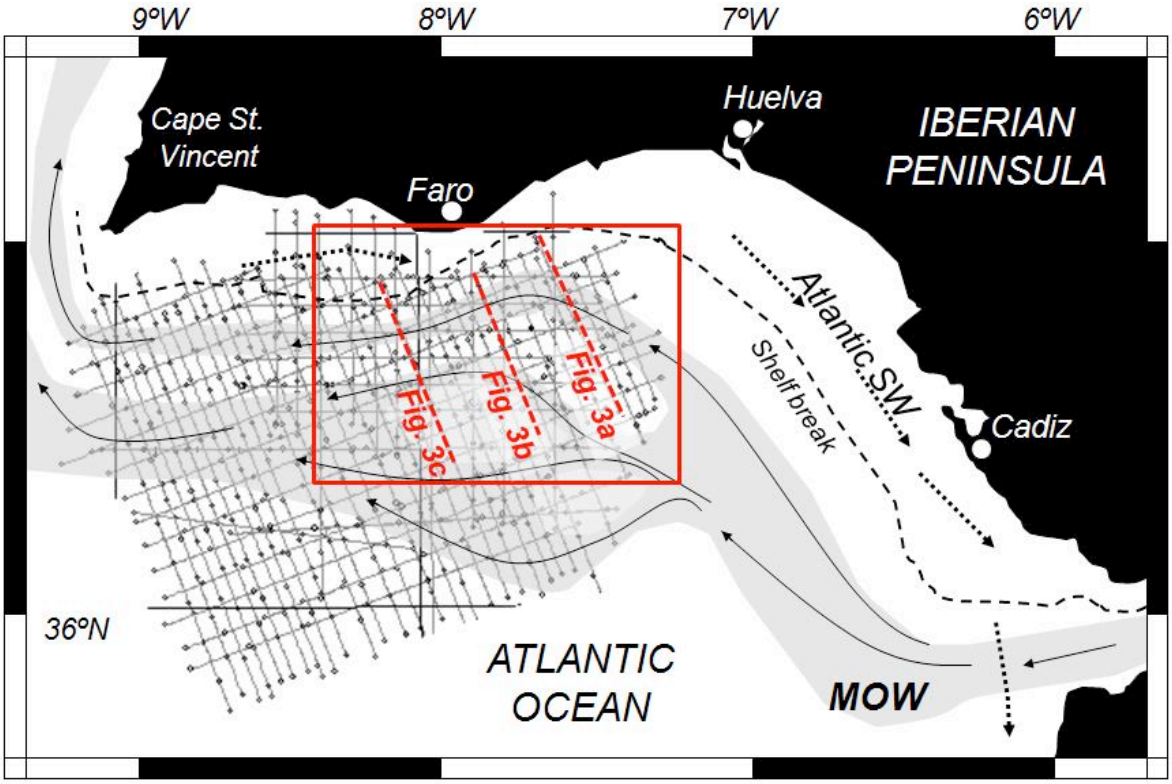


Figure 3.3: The study area is located along the northern margin of the Gulf of Cadiz and is influenced by the Mediterranean Outflow Water. The seismic surveys used for this study are indicated. Study area highlighted in box. Red dashed lines indicate position of Fig. 4.7. MOW = Mediterranean Outflow Water. Atlantic SW = Atlantic Surface Water.

3.1.2 Sediment Data

A number of sediment cores of different vintages and sampling resolutions were examined for this research. The main sedimentological work was carried out on three piston cores and one box core collected on the Scientific Cruise CONTOURIBER-1 (Fig. 3.1). The cruise collected complementary remote sensing data including swath bathymetry, seismic and parasound (Section 3.1.1). The three 12 cm diameter piston cores (PC06, PC04 and PC08) were divided into sections approximately one metre in length. The box core (BC05) was sub-cored and sliced at a resolution of 1 cm. From there, sub-samples were collected approximately 10 cc in volume. In total, approximately 14 m of gravity cores were collected. Due to the nature of soft sediment cores, additional analysis was carried out in order to enhance any sedimentary features. XRF and photography of the gravity cores was carried out at the Universitat de Barcelona, Faculty of Geology, followed by CT-scanning at the Universidad de Santiago de Compostela, Facultade de Veteranaria, Lugo. After logging and photographing, a total of 791 samples were collected for analysis at 2 cm resolution. An additional five superficial sediment samples were also analysed.

Six sites were drilled across the Gulf of Cadiz during IODP Expedition 339 which sailed 16th November 2011 – 16th January 2012 (Fig. 3.1). In total, 5.5 km of cores were recovered (Stow et al. 2013a). These sites targeted a variety of depositional environments across the Gulf of Cadiz, and the key site of interest in this study is U1388, located in the east. This site penetrated 253 m and recovered a total of 121 m of core (Expedition 339 Scientists 2012). In general, the top 10 m of the cores were examined in detail. Analysis on this core material was carried out at the Core Repository, MARUM, Bremen. This analysis, although not to the same high resolution as the gravity cores, consisted of logging, XRF, CT and grain size analysis. A final set of core analyses were carried out on historical piston cores collected at BOSCORF, National Oceanography Centre, Southampton. 25 metres of gravity core was logged from the lower slope of the eastern Gulf of Cadiz (Fig. 3.1). A detailed account of the methods used to examine these sediment cores and samples is outlined in below.

3.2 Methodology

3.2.1 Multibeam Bathymetry

A new bathymetric data-set was gathered using a deep water Multibeam Echosounder (Fig. 3.2 C). It extends and compliments the previously compiled Gulf of Cadiz bathymetric data-set (SWIM Map Team 2007; Zitellini et al. 2009) and leads to a new detailed understanding of the present day morphology of the eastern Gulf of Cadiz (Hernández-Molina et al. 2014). The bathymetric data was collected using a Multibeam Echosounder operating at 14.5 – 16 kHz

(CSIC Unidad de Tecnologia Marina). The device, mounted to the hull of the vessel, sends multiple narrow acoustic signal beams at varying angles in a fan arrangement towards the sea floor (De Moustier and Matsumoto 1993). The responding sea bed echo is received by the system's echo processor unit and converted to depth data. This equipment gives information on: 1) The bathymetric contours of the sea floor; 2) The micro-relief of the area; and 3) The sea bed material backscatter properties (i.e. surface roughness and density of substrate) (De Moustier and Matsumoto 1993). It will be used to map out the present day morphology of the sea floor.

3.2.2 Geophysical Methods

Seismic data has been used for marine and geological research and by the hydrocarbon industry to great effect since it was first used for exploration in the early 1900s (Mayne 1982). Post-acquisition and processing, geoscientists must interpret the data so that it makes geological sense. This is done based on three key assumptions: 1) Seismic reflections represent impedance contrasts (i.e. a change in density and elastic properties of a rock); 2) These impedance contrasts are representative of bedding; 3) Details in the seismic wave are a result of geological changes in facies and/or fluid content (Sheriff and Geldart 1995). Where possible, the interpretation has been supported by core data. The workflow used is standard to universal interpretation procedures and is outlined below for both data-sets.

3.2.2.1 CONTOURIBER-1 Acoustic Data-Sets

The CONTOURIBER-1 scientific cruise that sailed in October 2010 collected new 2D seismic survey, parasound, and bathymetric data-sets across the easternmost Gulf of Cadiz. A *parasound data-set* complements the piston cores acquired (Fig. 3.2). Parasound differs from seismic due to the frequency of the energy source used. The data shows varying acoustic characteristics across the study area such as penetration depth, amplitude, and lateral continuity. These relate directly to the substrate material and the extent of erosion versus uninterrupted deposition. The high-frequency acoustic source allows for the top metres of the subsurface to be imaged with high vertical and horizontal resolution (Grant and Schreiber 1990). This allows it to be integrated with piston core data to make conclusions on the lateral distribution of sediments in the study. Properties such as the acoustic character and penetration depth can give good indications of sediment type and depositional environment (Kuhn and Weber 1993).

An accompanying sparse *2D seismic data-set* of 27 lines was acquired using a single-channel mini-streamer targeting the shallow (up to approx. 2 km) sediment. 780 km of seismic data was prepared by geophysicists on-board the RV Sarmiento de Gamboa and loaded into the seismic software Petrel 2.7 for analysis (Fig. 3.2 A; C). The seismic sections are of moderate quality with varying signal/noise based on the water wave conditions at the time of acquisition. Penetration is on the order of 2 ms with a noted reduction in quality below 1.5 ms TWT. The survey acquisition and interpretation techniques are very similar to those outlined in Stoker et al. (1997). Full mapping of seismic units across this data-set is outside the scope of this work and has been examined in other studies by Hernández-Molina et al. (2014) and Llave et al. (*in preparation*). The data, however, can be used to give a long-term understanding for the depositional environment across the study area through the analysis of reflection relationships, and acoustic facies analysis (reflection frequency, continuity and amplitude analysis).

3.2.2.2 TGS 2D Seismic Data-Set

The data (Fig. 3.3) was compiled and uploaded to the interpretation software, in this case SMT Kingdom 8.5. The seismic data was thoroughly analysed for mis-ties and regions of poor data quality. In general, the survey shows moderate quality, reducing with depth. Poor resolution is observed at depths greater than 2.5-3 ms TWT. Additional zones of poor resolution can be accounted for by the presence of salt or gas, which are known to adversely affect seismic resolution (O'Brian and Gray, 1996; Løseth et al., 2009). Mis-ties were observed in the data-set, and these are mainly associated with regions containing structures of high dip. This is a typical problem encountered in 2D seismic. Additional mis-ties associated with more horizontal reflections are rare, and probably a result of poor static corrections and other processing procedures (Asad, 2009). The data was also checked for polarity and has been processed to European standard (negative events represent increased impedance contrasts). No velocity model is available for reliable time-to-depth conversion at this stage.

Only once data has been thoroughly assessed can an interpretation begin. This work builds on that carried out by Llave et al., (2001; 2007; 2011), Stow et al., (2002) and Hernández-Molina et al., (2006). Key discontinuities are identified in the subsurface which relate to oceanographic events along the margin. The data has been tied to industry boreholes Algarve-1 (36°54'06'',-7°33'59'') and Algarve-2 (36°48'36'',-7°30'55'') which were used to confirm the depth of major discontinuities. Although there will be increased risk in reflection mapping away from the boreholes, care was taken to map discontinuities characterised by strong reflections in seismic (Sheriff and Geldart 1995) and, more importantly, observing onlapping and downlapping as well as erosional truncations of reflections. Horizon flattening was regularly used to aid distinguishing between primary sedimentary features and tectonic events. Once picked, discontinuities were mapped. Eight key horizons have been mapped; the sea bed; six discontinuities within the Pliocene and lowermost Quaternary section, and the acoustic basement (Fig. 3.4). Contour maps for these horizons were produced using standard methods, along with isochron maps.

3.2.3 Sediment Facies

3.2.3.1 CT -Scanning

X-ray computed tomography, or CT-scanning can be utilised by marine geoscientists to image density differences within soft sediment cores. It provides a rapid and non-destructive technique for examining the internal structure of sediment cores in three dimensions (Mees et al. 2003) and reveals features that are otherwise impossible to visualise using conventional imaging or logging techniques (Orsi et al. 1994). It can be used to image bedforms, diagenetic features, bioturbation, ice-rafted debris, de-watering structures and stress fractures among other features (Mena et al. 2011; Rothwell and Rack 2006). Effectively, it can be used to image

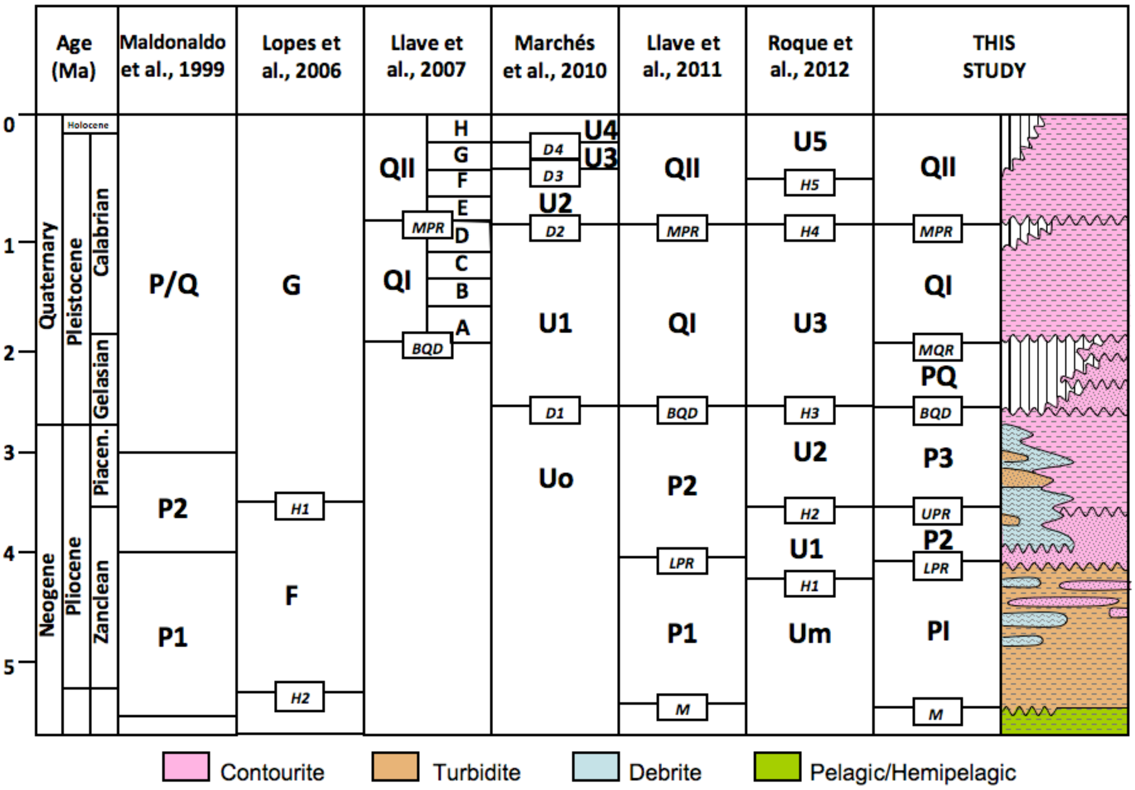


Figure 3.4: A number of past studies have been carried out in this region before. General consensus is nearing in the Quaternary section; however the Pliocene is refusing to yield a robust stratigraphy. This study identifies three units in the Pliocene and a highly eroded section in the Lowermost Quaternary. Modified from Llave et al. (2007c; 2011); Lopes et al. (2006); Maldonado and Nelson (1999a); Marches et al. (2010) and; Roque et al. (2012).

any feature within the sediment that has a radiographic density contrast to the surrounding sediment. This in turn can be used to interpret depositional environment, palaeoclimiatic conditions and diagenetic history of the deposit as well as aid correlation between core sites.

The three piston cores collected on the CONTOURIBER-1 cruise (PC04, PC06 and PC08) were selected for high resolution scanning (Fig. 3.5), and were transported to the *Facultade de Veteranaria* at the *Universidad de Santiago de Compostela*, Lugo (Spain) in February 2012. Each core section was run through a high resolution Hitachi ECLOS medical scanner (Fig. 3.5 A). The scanner uses a rotating scan system by which the X-ray source is rotated around the sample at speed and emits a beam to the receiver located on the opposite side of the sample (Fig. 3.5 B). The core is placed on a 'bed' in the centre of the rotating arm and moves in designated increments through the beam before the signal is mathematically reconstructed into a single image (Ashi 1995). Each core was placed on the scanner bed and an initial low-resolution 2D X-ray scan was carried out to ensure proper placement. The rotation of the X-ray source is initiated and the source is warmed before measurements are made at 0.625 mm increments. This provides high-resolution X-ray images of the core at a resolution of cube volume 0.2 x 0.2 x 0.625 mm (Fig. 3.5 C). The data was displayed in the freeware MRIcro where it can be manipulated in terms of colour, contrast and slice location in order to enhance any density contrasts within the sediment.

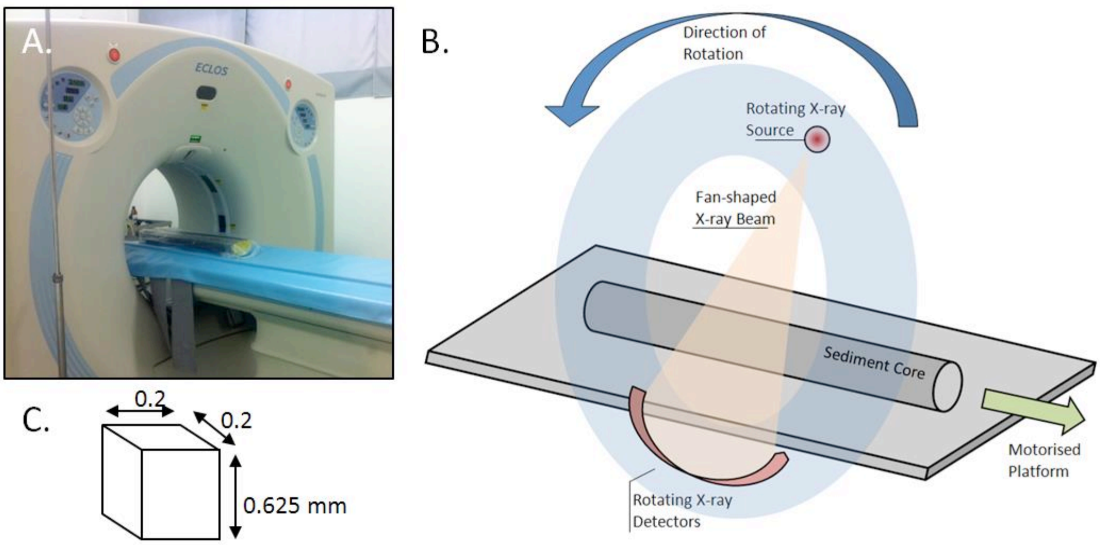


Figure 3.5: A) The high resolution Hitachi ECLOS medical scanner located at the Facultade de Veteranaria at the Universidad de Santiago de Compostela, Lugo. B) Schematic of the process of CT-scanning. C) Resolution of 3D scan.

3.2.3.2 Visual Logging

Additional to the CT-scanning, visual description was carried out on the three CONTOURIBER-1 piston cores, and other cores from the wider Gulf of Cadiz (Fig. 3.1). Conventional sediment logging was carried out in a variety of facilities across Europe as dictated by the sediment core storage localities.

1) Firstly, the three piston cores collected on the CONTOURIBER-1 scientific cruise of 2010 were slabbed and logged at the *Universitat de Barcelona* on the 6th – 11th June 2011. A total of 14 m of sediment (Table 3.2) was carefully logged and core photography, XRF and CT-imaging carried out. As a result, these cores are logged at the highest resolution of all those examined in this study.
2) IODP cores U1386, U1388, and U1389 (Fig. 3.1) were logged in the core repository in *MARUM*, *University of Bremen* in May 2012. Some additional low-resolution X-ray images were also acquired at this time on MARUM's General Electric CT Prospeed SX scanner, although these have not been used in this study (see Brackenridge et al. *in preparation*). Poor core recovery at sand-dominated site U1388 had resulted in only a 47.8 % recovery rate (Expedition 339 Scientists 2012). This is a significant decrease in core recovery when compared to sites located more distally from the Gibraltar Gateway: U1389 (77%) and U1386 (89%). As a result many key facies boundaries are absent, particularly at the coarsest sandy sections. Core U1388 does however provide the longest contourite sand core record from the eastern Gulf of Cadiz, with 121 m of core collected (Table 3.2). This study focuses on the most recent of sediments, primarily the top 10 m, however some older examples of facies types are also used.
3) Finally, logging was completed on five gravity cores in January 2014 collected by the NERC scientific vessel 'Discovery' in 2000 and one core collected in 1997 (Table 3.2). These are now stored at the *British Ocean Sediment Core Research Facility* (BOSCORF) in Southampton.

Cores were logged at various scales and resolution, depending on the length of core and the availability of accompanying data-sets. Despite this, care was always taken to document any broad grain size trends, erosional boundaries, sedimentary features, bioturbation features, facies, sediment colour changes and composition. Visual core description was backed up by smear slide analysis, the method and results of which are detailed in Chapter 5.

Cruise	Core	Lat (°N)	Long (°E)	Water Depth (m)	Core Length (m)
CONTOURIBER	BC05	35.845	-6.780	738	0.23
CONTOURIBER	PC04	35.736	-6.732	658	6.22
CONTOURIBER	PC04	35.736	-6.732	658	1
CONTOURIBER	PC06	36.305	-6.764	490	2.40
CONTOURIBER	PC08	35.821	-6.968	961	5.36
CONTOURIBER	PC08	35.821	-6.968	961	1
D225	D13075	36.251	-7.733	977	9.59
D249	D13896	36.043	-7.193	817	4.15
D249	D13889	36.122	-7.967	1580	1.18
D249	D13899	35.843	-7.483	1179	14.74
D249	D13900	35.81	-7.517	1297	18.11
D249	D13895	35.735	-7.717	1538	1.95
IODP 339	U1386	36.497	-7.453	561	850.6
IODP 339	U1388	36.161	-6.476	663	121
IODP 339	U1389	36.255	-7.167	644	1123.5

Table 3.2: The sediment cores used in the study of Gulf of Cadiz facies sequences.

3.2.4 Sediment Compositional Analysis

3.2.4.1 XRF Analysis

XRF analysis, or X-ray fluorescence describes the procedure by which a given material (in this case the sediment) is bombarded by gamma waves (electromagnetic waves of length 10^{-10} m and frequency 10^{18} Hz) from a radioactive source (Röhl 2010). The bombarded atoms react by emitting an inner electron and as a result the atom becomes unstable. Outermost electrons must transfer inward towards the nucleus to regain atom stability. The emitted waves from the now excited atoms reach the receiver as modified X-rays that have a characteristic signal representing the chemical composition of the measured material. Between the source and the receiver, the waves travel through a hollow helium-filled prism in order to reduce any absorption of the emitted waves into the air (Fig. 3.6 B). The read-out for the analysis will be a XRF spectrum with peaks representing 'number of counts' of a certain kiloelectron volt (keV) value (Fig. 3.6 C).

XRF analysis is a common method used in geochemical analysis as it provides a rapid non-destructive analytical tool that requires minimal preparation at a cost-effective price (Shackley 2011). It has been used by authors to gain information about the grain size, palaeoceanographic conditions and diagenetic history of the sediment (Fütterer 2006; Richter et al. 2006). Studies have linked increased Ca content with interglacial periods and increased Fe with glacial periods on a Milankovitch timescale (Richter et al. 2006). Whereas other studies have shown that Zirconium/Aluminium (Zr/Al) peaks can be linked to Dansgaard–Oeschger events (Bahr et al. 2013). Other applications to XRF analysis on marine cores include heavy mineral investigations and provenance studies (Elsow 1932; McLennan et al. 1993), organic matter content analysis (Bahr et al. 2013) and oxygenation studies (Janson et al. 1998).

In this study, the three piston cores (PC04, PC06 and PC08) were transported to the *Universitat de Barcelona* for opening (slabbing) and immediate core imaging and XRF analysis (Fig. 3.6 A). The three piston cores were analysed over a period from the 6th to 11th June 2011 in the *Faculty of Geology*. The counter used in this study was an Avaatch XRF Core Scanner. It adheres to standard measuring principles. First, the machine was calibrated using ground samples of known composition. Cores were prepared by ensuring the surface was smooth and flat. It should be noted that the sediment surface will never be totally solid or homogeneous, and therefore the accuracy of the data will never be complete. This is of particular importance in highly sandy sections where large particles dominate the return signal and pore-water readings will play a more important role (Janson et al. 1998). A specially manufactured polyester film was applied to the sediment surface in order to retain the sediment and liquid content and to avoid contaminating the scanning equipment. Initial and final sample depths were input to the computer software and a sample resolution of 10 mm was run. Sampling

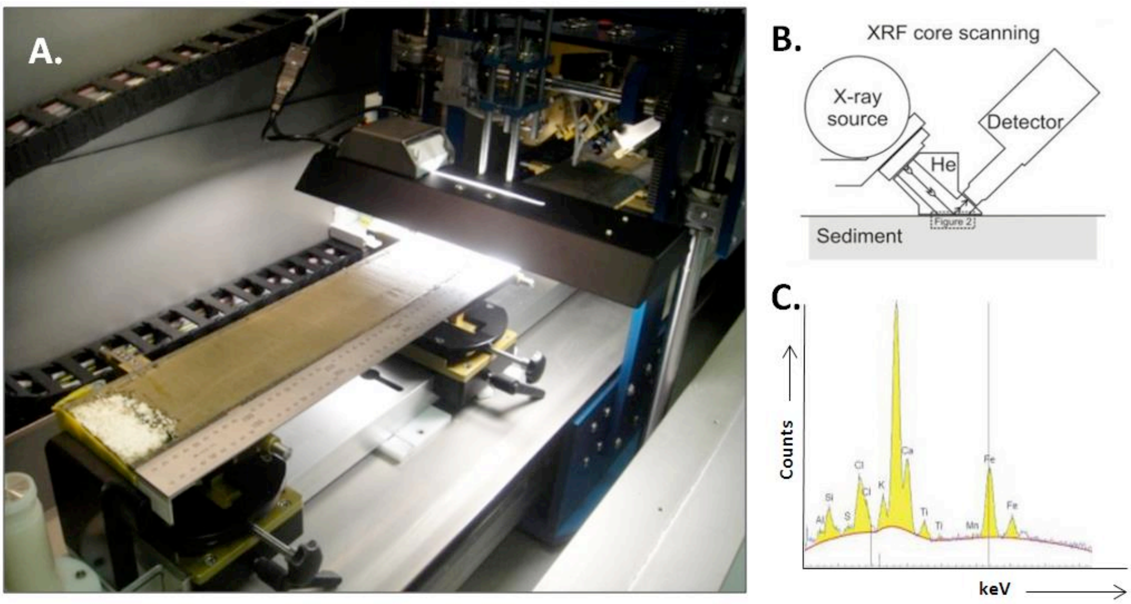


Figure 3.6: XRF scanning theory. A. A core section being imaged in the Avaatch XRF Core Scanner located in the Universitat de Barcelona; B) Schematic of the XRF scanning equipment; C) The output of data, where elements have signature keV energies and are plotted against 'counts' registered. Images B) and C) from Rõhl (2010).

was run at 10 keV, energy capable of measuring light elements of atomic number 13-26. For additional elements to be measured, energies of up to 50 keV must be measured. The output of element 'counts' is difficult to translate into an accurate reading of element concentrations due to the heterogeneity of the core and the limited energy reading ranges. Therefore, ratios are commonly used to show downhole changes and aid correlation between cores (Weltje and Tjallingii 2008).

3.2.4.2 Smear Slide Analysis

Smear slide analysis provides sedimentologists with a rapid method to observe the composition and texture of a sediment at high resolution (Tucker 1991). For this, standard smear slide preparation methods were used; a small volume (<0.1 cc) of sediment from the core is combined in water to disaggregate, and spread to a uniform thickness across a glass sediment slide. Upon drying (usually carried out on a hot plate) the sediment is bound to the glass slide using an optical glue (in this case EUKITT mounting glue) and a protective glass cover slip is carefully placed on top, and left to dry.

The analysis of the sediment mineralogy compliments the XRF analysis by visually examining the sediment to further understand the chemical response. Multiple smear slides were produced from the sediment samples and examined for composition under optical microscope. The sediment was sampled at regular depth intervals, and at key bed boundaries that showed a distinct change in facies. Analysis was carried out under an Olympus BH2-UMA petrological microscope and was photographed using an Olympus 5.1 megapixel C-5060 camera. Sediment parameters to be assessed were grain morphology (shape, roundness) and sediment composition (terrigenous, biogenic, clay – see Table 3.3). This was combined with the grain size analysis results (mean grain size and sorting) to give a full picture of the sediment characteristics for each sample.

Grain morphology assess the average shape, spherity and roundness of the sediment grains in the sample (Tucker 1991). There are formulae for the precise measurement of grains in the literature, however, analysis here was done qualitatively. The *spherity* is defined as the evaluation of how close the grain is to a spherical shape. This is closely related to the grain *shape*, which examines the grain along three axes and defines it as oblate, equant, bladed or prolate (Fig. 3.7). This can be an indication of sediment maturity, or can be controlled by the sediment composition (e.g. biogenic spine material will tend towards rod or prolate in shape). Finally, the *roundness* concerns the smoothness of curvature of any grain corners or edges. They are classed into 5 defined groupings from very angular through well rounded (Pettijohn et al. 1987) and give an indication of the maturity, or distance from sediment source of the material. Sediment composition identification was aided using reference materials (Haq and Boersma 1978; Rothwell 1989; Stanley 2011). Key components identified are indicated in Table 3.3. Quantities of each are given as descriptive terms as used by the shipboard scientists in the Proceedings of the IODP 314/315/316 (Kinoshita et al. 2009). Descriptive terms are a function of estimated percentage abundance as determined using a visual comparison chart (Rothwell 1989). Terms and approximate percentages are as follows;

- D = dominant (> 50 %)
- A = abundant (> 20-50 %)
- C = common (> 5 - 20 %)
- P = present (>1 - 5 %)
- R = rare (0.1 - 1 %)
- T = trace (<0.1 %)

The grain morphology and sediment compositional information was compiled along with the grain size analysis to give a complete summary of the sediment at each sample depth.

Terrigenous	**Quartz**	
	Feldspar	
	Ferromagnesian Minerals	*Amphiboles, Olivines and Pyroxenes*
	Micas	*Biotite, Muscovite*
	Detrital Carbonates	
	Heavy Minerals	*e.g. Apatite, Epidote, Garnet*
	Other Terrigenous minerals	*Commonly Glauconite*
Biogenic	Bryzoa	
	Forams	*Dominantly from the Globorotalia foraminifera family*
	Shell Fragments	*Bivalve debris. No intact specimens found*
	Siliceous material	*Radiolaria and sponge spicules and diatoms all observed*
	Nannofossils	*Coccoliths ; pseudoemiliana lacunose and gephyrocapsa oceanic most common*
	Other	*e.g. algae, ostracodes etc*
	Clay	*Clay minerals where resolvable under the petrological microscope plus the very fine unresolved fraction.*

Table 3.3: Sediment composition components were sub-divided in to the following groups; identification was aided using Rothwell (1989) and Haq and Boersma (1978).

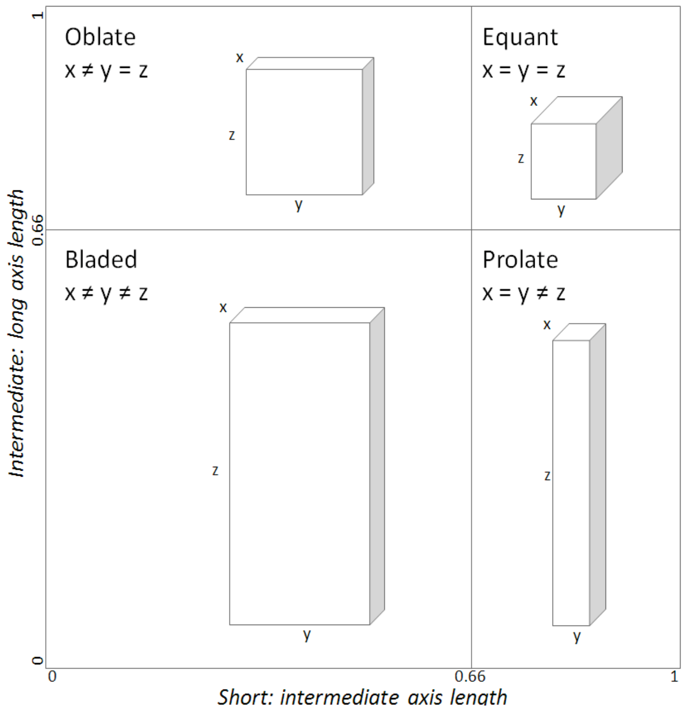


Fig. 3.7: Grain shape classifications based on Nichols (2009).

3.2.5 Sediment Texture

For the textural analysis of the CONTOURIBER-1 cores, samples of 10 cm^3 in volume were taken from the piston cores (PC04, PC06 and PC08) every 2 cm for grain size analysis. In total 791 samples were collected and analysed at the *Environnements et Paléoenvironnements Océaniques, Université Bordeaux* in November 2012. The analysis was done using laser counting methods on a Malvern Particle Size Analyser machine. An additional 23 samples from the box core BC05 were analysed using sieving methods at *Heriot-Watt University*.

Grain size can reveal information about sediment origins and history of its transportation and depositional environment (McCave and Syvitski 1991). It has even been claimed that it is the single most important property of any marine sediment (Krank and Milligan 1991) and has important implications for the porosity and permeability of the sediment upon burial. Analysis can be of great importance in the petroleum industry for the prediction of depositional environment in the absence of sediment core (Glaister and Nelson 1974). Much work is still required to apply the grain size analysis of contourite sediments to its full potential, although some studies do exist in the literature (Alejo et al. 2012; Huvenne et al. 2009; McCave 2008; Stow et al. 2008).

The principal method used in this study was laser diffraction. This involves passing a representative sample of sediment in suspension past a beam of laser light. The light will be scattered by the particles to varying extent and received in a modified form at the receiving lens and detector (Fig. 3.8). The diffraction angle of the laser beam off the sediment particles is determined by the particle size; the larger the particle, the smaller the diffraction angle (Malvern Instruments Limited 2012; McCave et al. 1986). Focusing lenses define the range of grain sizes that may be measured. Modern laser diffraction devices can use both a red-light and a blue-light to ensued maximum range of recorded diameter sizes (Fig. 3.8). Through decoding, the detector produces particle size distributions from the collected diffracted light data (Cooper 1998). A distribution of grain diameters can be acquired in a matter of minutes, providing much faster and more detailed grain size data when compared to many other techniques such as sieving, settling tubes, or image analysis (Martins 2003). The processed grain size output is a volume weighted distribution as opposed to a number weighted (Fig. 3.9). That is to say that the contribution of each particle within the distribution results directly relates to the volume of that particle not just the fact that it is present (Malvern Instruments Limited 2012).

The standard procedure for grain size analysis in laser counters was used. The first step is to remove the organic matter within the sediment. This is done by diluting a small amount of sediment (one to two grams) in water and then adding a small quantity (approx. 5 ml) of 30 % hydrogen peroxide (H_2O_2). The beakers are left to stand until all reactions (frothing) have ceased. This may be 0.5 to 2 hours depending on the amount of organic matter present. Once frothing has stopped, the beakers are kept in a fume cupboard and gently warmed in a hot bath (at 60-70°C) with additional H_2O_2 added if necessary until no more reaction is observed. The beakers are removed from the bath and cooled in a fume cupboard. Once cool, a 0.6 % solution of sodium hexametaphosphate (calgon) is added as a dispersant at a ratio of

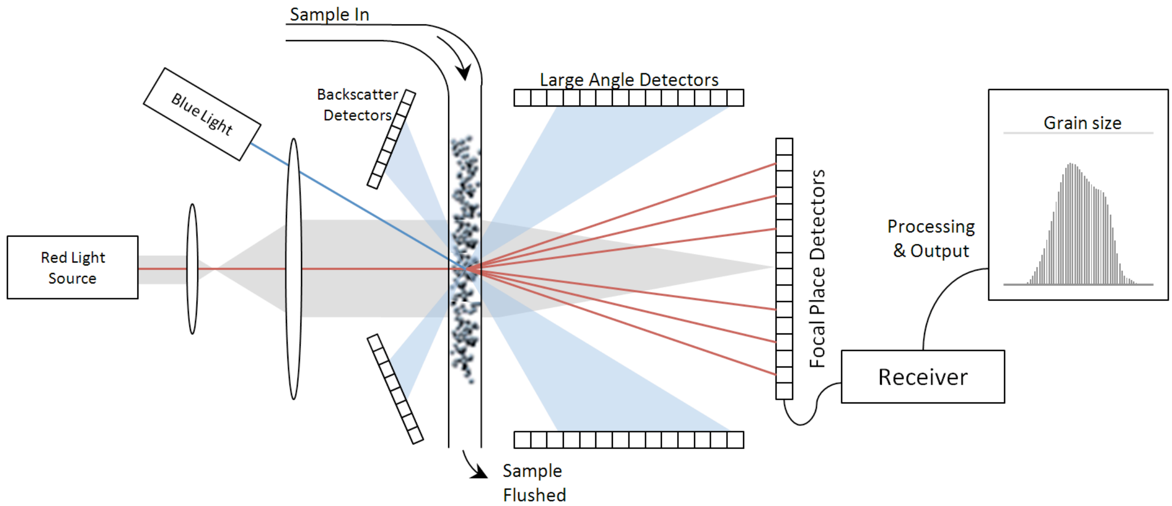


Figure 3.8: Particle size analysis by laser diffraction. Modified from Malvern Instruments Limited (2012); McCave et al. (1986).

approximately 5 ml sodium hexametaphosphate to 50-100 ml distilled water per each estimated gram of clay. The solution is treated in an ultrasonic bath for 10 minutes or longer if particularly clay-rich and refusing to separate. Finally, the samples can be added to the Malvern Particle Analyser. In this case an automated dispenser allowed for numerous samples to be analysed with automatic rinsing of the machine between analyses. An automatic read out is exported giving the range of grain sizes from 0.05 µm to 700 µm – or clay up to medium/coarse sand.

Additional grain size sieving methods were used where samples were too coarse for the laser counters (Lewis and McConchie 1994). This consisted of careful preparation of the sediment in the same manner as the laser counter samples. Due to the clean nature of the sand samples, the mud portion was not removed and analysed separately. Before analysis, the sample must be dried, in this case in an oven at 80°C overnight. The sample is weighed before being placed in a sieve nest and shaken for a consistent amount of time on a sieve shaker. The sieve nest here measured grain size distribution in 0.5 phi steps where possible, from 63 µm to 4000 µm, and was processed on an Endecotts sieve shaker for 30 minutes. The fraction from each sieve can then be weighed the grain size distribution calculated.

The results were compiled in Microsoft Excel. Distributions are given in a geometric (volume) scaling rather than an arithmetic (number) scale to ensure there is equal emphasis on changes in clay, silt and sand content in the histogram (Fig. 3.9) (Blott and Pye 2001b). Key statistical trends measured were: 1) Mean (and mode) grain size; 2) Grain size sorting; 3) Grain size distribution skewness; and 4) The kutosis, or concentration of grains around the mean. The formulae used for these measurements and the cut-off values for defining the sorting, skewness and kurtosis are shown in Figure 3.10. There are many different methods of grain size statistical analysis, each with their own advantages and disadvantages. All analysis was

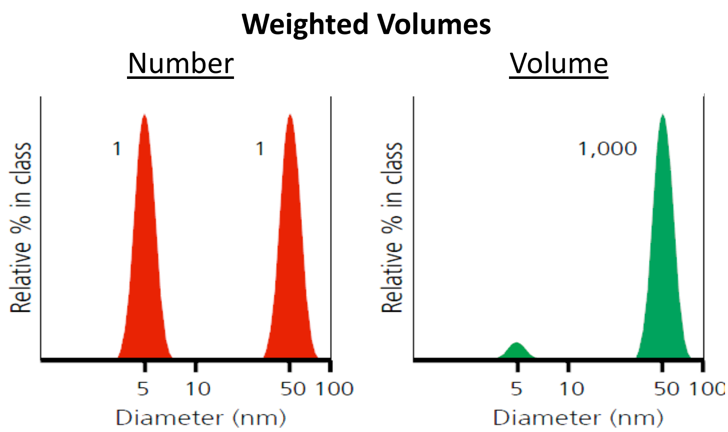


Figure 3.9: Number weighted vs. volume weighted. From Malvern Instruments Limited (2012).

carried out in the software GRADISTAT (Blott and Pye 2001a) using the geometric graphical method as laid out by Folk and Ward (1957) to ensure that each set of analysis can be directly compared to others in the study. Cumulative frequency curves were also created in order to clearly visualize differences in distribution. After calculations of the essential statistics, data can be compared using cross plots to say something of the sediment transport and depositional environment, particularly where sandier sediment is found (Folk 1964; Martins 2003). The scale and sediment classes as defined by (Wentworth 1922) was used, as shown in Appendix 6.

3.2.5.1 Mean Grain Size

The mean grain size, grain size sorting, skewness and kurtosis (Fig. 3.11) have long been used as the fundamental grain size parameters to fully describe the sediment and aid facies identification (Blott and Pye 2001b; Glaister and Nelson 1974; Kranck and Milligan 1991; Martins 2003; Visher 1969). These were calculated using the program GRADISTAT (Blott and Pye 2001a) which is capable of calculating a suite of statistics using method of moment and graphical measurements. Each analysis method has its own set of pros and cons (Folk 1964), and this study uses the Folk and Ward (1957) graphic measurements on a metric scale as recommended by Blott and Pye (2001b) for its "robust basis for routine comparisons of compositionally variable sediment" and the ease of converting values into descriptive terms (Fig. 3.10). Central tendencies (the mean, mode and median) of the sediment distribution give

(e) Geometric (modified) Folk and Ward (1957) graphical measures

Mean

$$M_G = \exp \frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$$

Standard deviation

$$\sigma_G = \exp\left(\frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6{\cdot}6}\right)$$

Skewness

$$Sk_G = \frac{\ln P_{16} + \ln P_{84} - 2(\ln P_{50})}{2(\ln P_{84} - \ln P_{16})} + \frac{\ln P_5 + \ln P_{95} - 2(\ln P_{50})}{2(\ln P_{95} - \ln P_5)}$$

Kurtosis

$$K_G = \frac{\ln P_5 - \ln P_{95}}{2{\cdot}44(\ln P_{25} - \ln P_{75})}$$

Sorting (σ_G)		Skewness (Sk_G)		Kurtosis (K_G)	
Very well sorted	<1·27	Very fine skewed	−0·3 to −1·0	Very platykurtic	<0·67
Well sorted	1·27–1·41	Fine skewed	−0·1 to −0·3	Platykurtic	0·67–0·90
Moderately well sorted	1·41–1·62	Symmetrical	−0·1 to +0·1	Mesokurtic	0·90–1·11
Moderately sorted	1·62–2·00	Coarse skewed	+0·1 to +0·3	Leptokurtic	1·11–1·50
Poorly sorted	2·00–4·00	Very coarse skewed	+0·3 to +1·0	Very leptokurtic	1·50–3·00
Very poorly sorted	4·00–16·00			Extremely leptokurtic	>3·00
Extremely poorly sorted	>16·00				

Figure 3.10: Formulae used and cut-off values for descriptive terms for sorting, skewness and kurtosis used. From Blott and Pye (2001b). Px is the grain diameter percentiles in metric units.

a good first indication of the relative flow velocity at the time of deposition (Kranck and Milligan 1991). The average, or mean grain size was calculated in this study using the formula;

$$M_G = \exp \frac{\ln P_{16} + \ln P_{50} + \ln P_{84}}{3}$$

The mode (most common grain size) was also calculated, and where grain size distribution was bimodal or trimodal the subsidiary modes were also noted.

3.2.5.2 Sorting

In essence, the standard deviation calculates the 'spread' of the distribution from the mean value (Fig. 3.11 A). This is, in turn, linked to the velocity and variability of the bottom current mass at the time of deposition, and/or the available sediment supply (Kranck and Milligan 1991). The standard deviation equation used by Folk and Ward (1957) evaluates the sediment sorting using their equation (below) and then assigns a class from extremely poorly sorted through very well sorted to the sediment sample.

$$\sigma_G = \exp\left(\frac{\ln P_{16} - \ln P_{84}}{4} + \frac{\ln P_5 - \ln P_{95}}{6{\cdot}6}\right)$$

3.2.5.3 Skewness and Kurtosis

The skewness is a measure of the direction and magnitude of the spread of the data to either side of the average value (Blott and Pye 2001b). Preferential spread to the left of the median constitutes a negative skew, and to the right, a positive skew (Fig. 3.11 B) and is calculated in this study using the below equation;

$$Sk_G = \frac{\ln P_{16} + \ln P_{84} - 2(\ln P_{50})}{2(\ln P_{84} - \ln P_{16})} + \frac{\ln P_5 + \ln P_{95} - 2(\ln P_{50})}{2(\ln P_{25} - \ln P_5)}$$

The classification of the skewness was defined by Folk and Ward (1957) based on measurements made in phi scales. This study uses metric scales and therefore care must be taken to extrapolate results across the units. Positive skewness values, named a 'coarse skew' indicate a tail of coarse sediments from the normal curve. Negative skew values represent a 'fine skew' or tail of fine sediments (Fig. 3.10; 3.11 B). This is the opposite from conventional statistical skew values and care must be taken to note this during the interpretation.

Kurtosis considers the ratio between the spread around the mean grain size versus the distribution 'tails' (Fig. 3.11 C). It is often referred to as measure of the 'peaked-ness' or the concentration of values around the mean (Blott and Pye 2001b) and has been calculated using the Folk and Ward (1957) equation;

$$K_G = \frac{\ln P_5 - \ln P_{95}}{2{\cdot}44(\ln P_{25} - \ln P_{75})}$$

The classification scheme associated with this equation has been used where platykurtic indicates a broad spread away from the mean and leptokurtic signifies a high concentration of values around the mean (Fig. 3.10; 3.11 C).

When plotted against kurtosis, skewness can be useful for inferring the origin of sediments (Folk 1964). Skewness vs. kurtosis has been used in numerous studies in an attempt to distinguish depositional environments (Martins 1965; Mason and Folk 1958; Shepard and Young 1961; Ananiadis et al. 2004) with limited success.

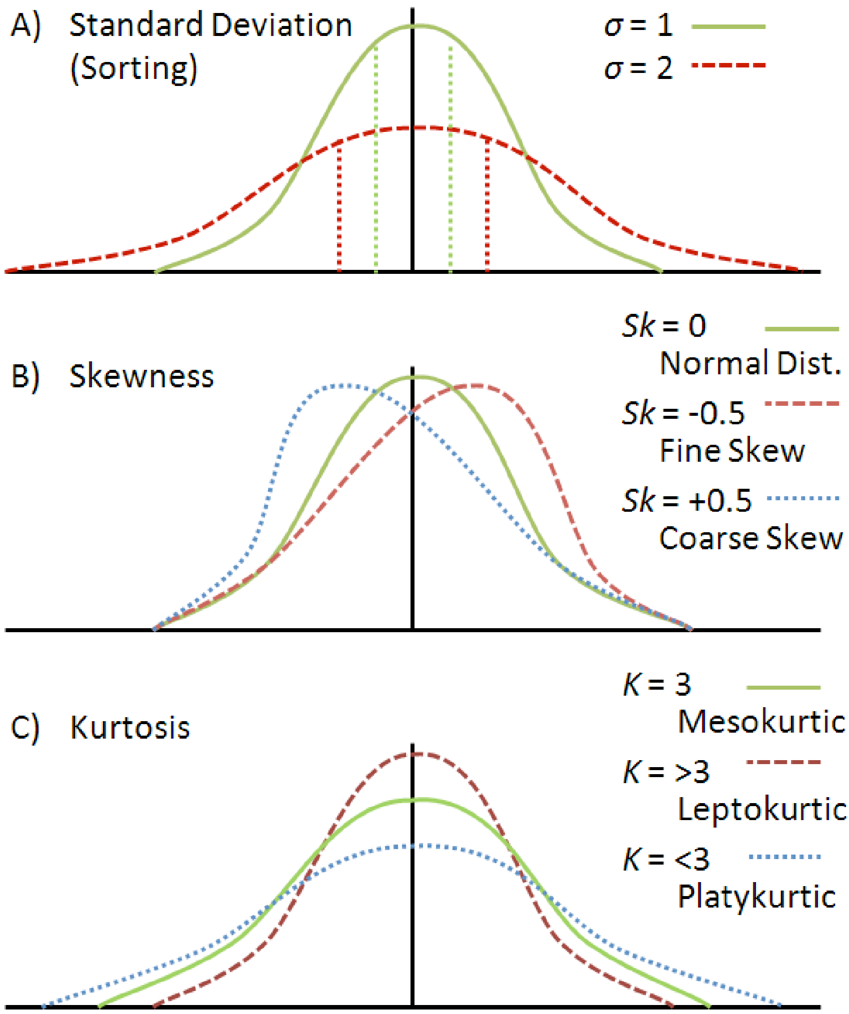


Figure 3.11: Distribution curves for sorting, skewness and kurtosis descriptive terms.

3.2.5.4 Cumulative Frequency Curves

Traditionally, cumulative curves have been used to perform statistical analysis using graphical procedures, albeit when plotted using the probability percentage ordinate rather than the arithmetic percentage (Folk 1964). Nowadays, computers allow such calculations to be done 'en masse' quickly and precisely, although cumulative curves can still give some useful and interesting insight to the data. In other studies, changes in the cumulative frequency curve have been linked to changing transport mechanisms (Stow et al. 2008).

3.2.6 Dating

Radiocarbon dating is a hugely popular, relatively inexpensive, and accurate method for dating an array of materials that are younger than approximately 50,000 years. It has been widely utilised in archaeological studies (Taylor 1987) and Quaternary science Lowe and Walker 1997) to great effect. It works to assess the ^{14}C isotope content of matter. In the atmosphere ^{14}C combines with oxygen to create carbon dioxide, and therefore becomes part of the carbon cycle to be used in the process of photosynthesis or ingestion of plant material (Walker 2005). There are three carbon isotopes; two stable (^{12}C and ^{13}C) and one unstable (^{14}C). Over time, the unstable ^{14}C decays towards a stable form (^{14}N). It is by understanding the rate, or half-life, of this radioactive decay that allows us to use ^{14}C in dating (Fig. 3.12 A). The ocean is a major carbon sink, storing 95% of the world's carbon (Walker 2005). As a result, organisms (nannofossils, molluscs, foraminifera etc.) take up a portion of this ^{14}C which is preserved in their carbonate tests (Fig. 3.12 B). Upon death and burial, these organisms are no longer able to exchange carbon and isotope decay is initiated. By understanding the rate, or half-life, of this radioactive decay, the date that the organism was deposited in the sediment can be determined (Walker 2005), thus giving the age of the sediment.

The preparation of sediment samples for radiocarbon dating is relatively time consuming and requires a great deal of care to avoid sample contamination. First the sample is taken from the sediment core. A sample volume of no less than 20 cc is recommended to ensure sufficient carbon content to be measured. The carbon to be measured is contained within the foraminifera tests, and therefore the foraminifers must be separated from the sediment for the analysis. Firstly, the samples are carefully cleaned and the fine section removed by settling. After drying the remaining sediment, sieving is used to collect the portion that is greater than 125 µm where the foraminifers are most prolific. To reduce the error in ^{14}C dating to a minimum, mono-specific foraminifera species of similar size should be used where possible since the isotopic fractionation differs between the species, and life-stages of an individual foram. In this study, the planktonic foraminifera species of *G. bulloides* (Fig. 3.12 B) and *G.*

ruber were targeted. Once picked, the foraminifers are then analysed for their ^{14}C isotope content. This was carried out at the *Universities Environmental Research Centre* (SUERC) Radiocarbon Dating Lab in the UK (Fig. 3.12 C) and the *Laboratoire de Mesure du Carbone 14* (France) using accelerator mass spectrometry (AMS) methods. The AMS records the ratio of ^{14}C to the stable ^{12}C and ^{13}C and uses this to calculate the extent of decay and therefore date of the sample. This involves converting the sample to graphite and bombarded by caesium ions (Cs^+). The result is a release of negative carbon atoms (C^-) which are accelerated through the AMS by magnets until electrons are removed and they are collected as C^{3+} ions of slightly different mass depending on the isotopic number (Walker 2005). The difference in mass of $^{12}C/^{13}C$ and ^{14}C can then be calculated.

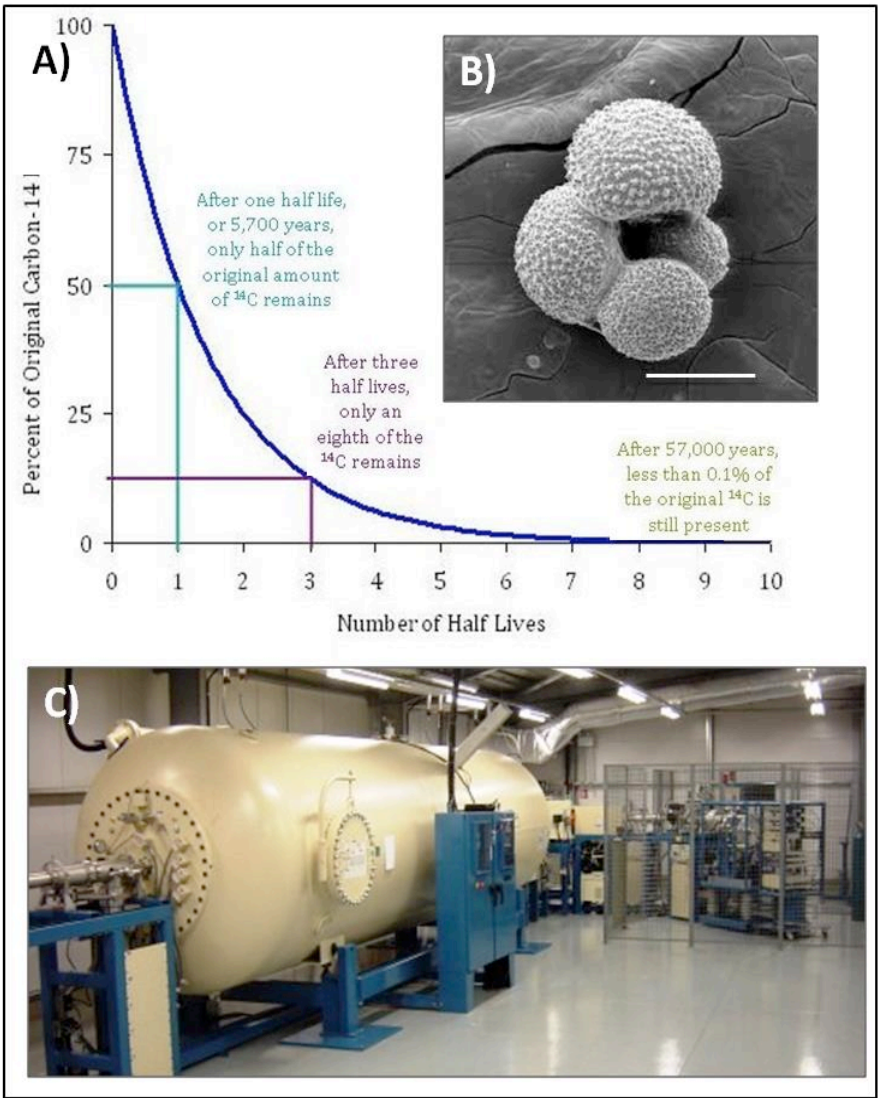


Figure 3.12: A) Radioactive decay (half-life) of ^{14}C. Decay is exponential over time. B) The plantonic foraminifera G. bulloides, used in this study. Scale bar 100 µm. Both images from (NOAA n.d.) C) The 5 MV accelerator mass spectrometer at the SUERC Radiocarbon Facility, East Kilbride, Scotland (SUERC n.d.).

Results

4 Seismic Analysis

This study utilises two sets of acoustic data from the Gulf of Cadiz. Firstly, in the eastern Gulf of Cadiz, 2D (airgun) seismic survey, parasound, and bathymetric data-sets accompany sediment core data (see Chapter 3). A total of ~780 km of seismic and parasound was acquired and forms the main tie between core data and depositional environment in the Quaternary and Late Neogene succession (Fig. 3.2). The bathymetric data gives a good impression of the modern day morphology and sedimentary stacking patterns of the margin. In addition to this, the seismic data-set was used to examine the controls on contourite deposition and the acoustic response of sediments in high-energy contourite environments. Secondly, located in the north of the Gulf of Cadiz, along the Algarve margin, two seismic surveys acquired by TGS are made up of a total of 95 lines, between 160 and 320 km WNW of the Gibraltar Gateway (Fig. 3.3). A mixed system is identified with an associated buried sandy sheeted drift which will be characterised. The results of the analysis on these data-sets are documented here-in.

4.1 CONTOURIBER Acoustic Data

This new data-set is being investigated by a collaborative body of scientists from Belgium, France, Spain and the UK. As such, there is a wide variety of research aims for this data. *This* research thesis endeavours to use it to;

1) Map the main morphological features of the present day using the new bathymetric data-set to identify the depositional environments across the eastern Gulf of Cadiz.
2) Correlate the core and parasound data to assess contourite sand acoustic response.
3) Use key seismic lines to assess the main depositional environments where contourite sands are deposited and use this to support the evidence from the sediment data.

4.1.1 Acoustic Facies

Figure 4.1 outlines the variety of parasound acoustic facies. Four key facies are identified: 1) A weak, low amplitude facies regularly showing a hyperbolic response; 2) A laterally variable facies with locally very high amplitude response and low penetration depths; 3) A laterally continuous, moderate- to high- amplitude facies with moderate penetration and parallel reflections observed in the subsurface; and 4) Laterally continuous low amplitude reflections with good penetration and reflection continuity with onlap relationships. These differences are directly linked to sediment type on the sea bed and near-surface substrate, and the depositional environment at the time of formation.

4.1.2 *Morphosedimentary Features*

Zooming out of the parasound data also gives clues to the depositional processes ongoing in the study area (Fig. 4.2). Although a full interpretation of the seismic units and their distributions is outside the scope of this study (Llave et al. *in preparation*), and of a different vertical resolution to that of the gravity cores used, the seismic data gives good clues to the current and palaeo-depositional environment of the region as well as a regional picture of both morphologies and sedimentary stacking patterns. The analysis of two seismic lines (Cadiz-21 and Cadiz-17) gives a good impression of past evolution of the margin where the gravity cores were collected (Fig. 4.3). They show a number of interesting features. Firstly they highlight the modern day sea bed morphology and support the depositional contourite drifts and erosional contourite channels and terraces that are seen in the bathymetric data (Hernández-Molina et al. 2014). Secondly, they show that although the margin morphology has evolved over time, contourite processes have dominated the margin for a geologically significant time (since late Pliocene / base of the Quaternary according to studies by Hernández-Molina et al. (2014). Finally, they show the relationship between the observed substrate features and the modern day oceanographic data as collected over the last four decades (Fig. 4.3) (Schlitzer 2013).

The bathymetric data has been integrated with previous published regional data (SWIM Map Team 2007; Zitellini et al. 2009) to map the main morphological features. These compliment the associated subsurface data to make firm conclusions on the depositional environments across the study area (see Chapter 6).

4.2 TGS Seismic Surveys

The picking of key seismic reflections (Fig. 4.4) and the analysis of seismic units and facies in the TGS seismic survey located in the north of the Gulf of Cadiz reveal a complex system that is evolving over both space and time. They are used in the discussion chapters to;

1) Distinguish depositional processes in the Pliocene section of the northern Gulf of Cadiz.
2) Characterise a buried sandy mixed system in the subsurface.
3) Identify key controls of the deposition of sand-rich contourites.
4) Assess the importance of mixed systems in forming potential hydrocarbon reservoirs.

The above points will be discussed further in the Interpretation and Discussion (Chapters 6-9).

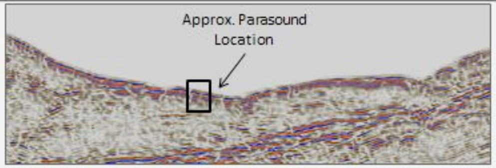
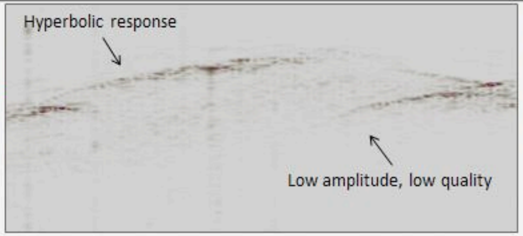
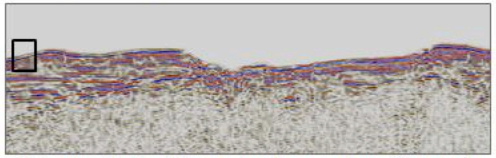
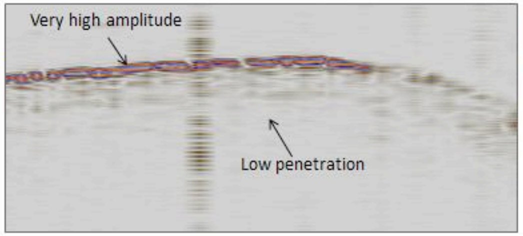
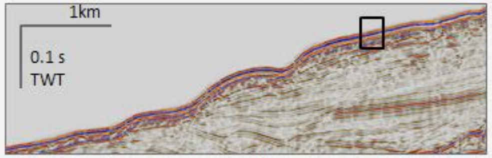
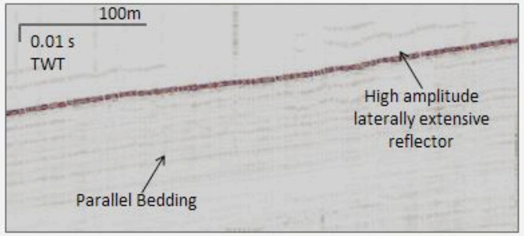
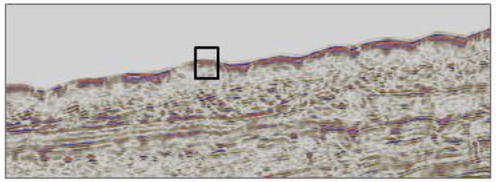
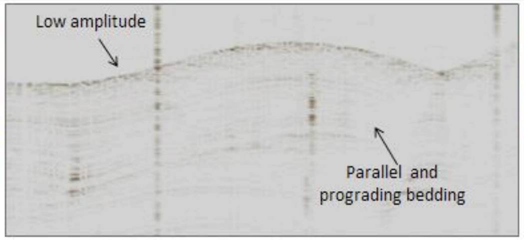
Acoustic Facies	Seismic Response	Parasound Response	Acoustic Signature
1	 Erosional surface with terraces. Truncations and down-cutting upslope, deposition downslope.		Highly complex acoustic response. Hyperbolic parasound with varying amplitude and low lateral continuity. Indicates short-lived bedforms within an erosive/non-deposition environment.
2	 Bright amplitude with erosional truncations (furrows) and prograding depositional features (sand ribbons). Poor resolution below ~0.1 sec TWT.		Locally very high seabed reflector indicates high sand content. The result is a poor penetration depth. Erosional furrow features are seen with depositional sand waves/ribbons.
3	 Smooth high amplitude parallel bottom reflectors with furrow indentations. Complex along-slope/down-slope interaction onlap surfaces.		High amplitude laterally continuous sea bed reflector. High frequency planar bedding visible in parasound. Seismic shows complex onlap & erosional truncation relationships.
4	 Migrating sediment waves and laterally-extensive erosional surfaces.		Low amplitude, high frequency, laterally continuous reflections indicate more mud-rich bedded facies. Progradation is seen indicating migrating sediment waves.

Figure 4.1: Seismic and acoustic facies across the eastern Gulf of Cadiz.

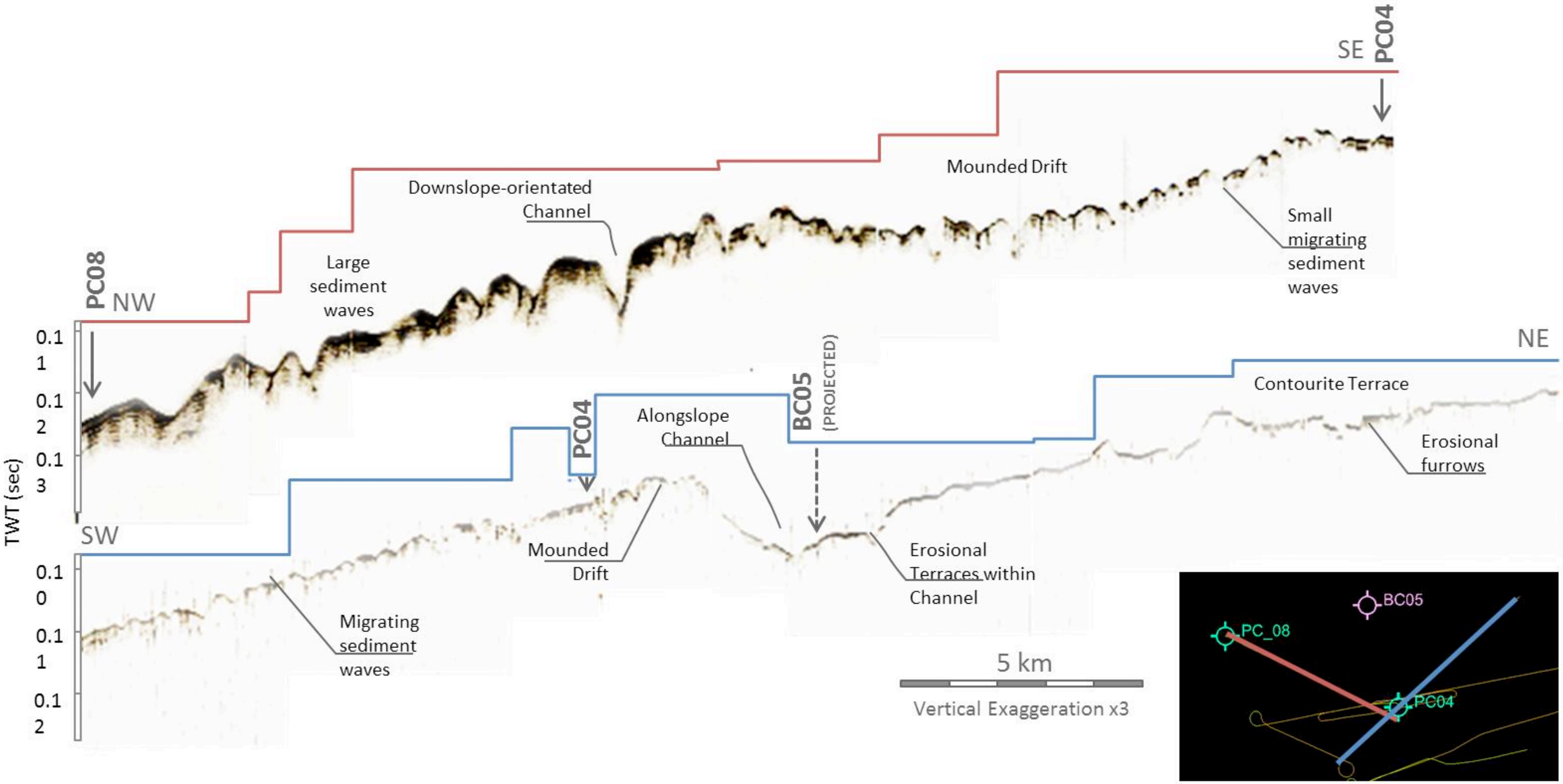


Figure 4.2: Two interpreted parasound lines from the lower slope of the eastern Gulf of Cadiz. Locality shown in Fig. 3.2.

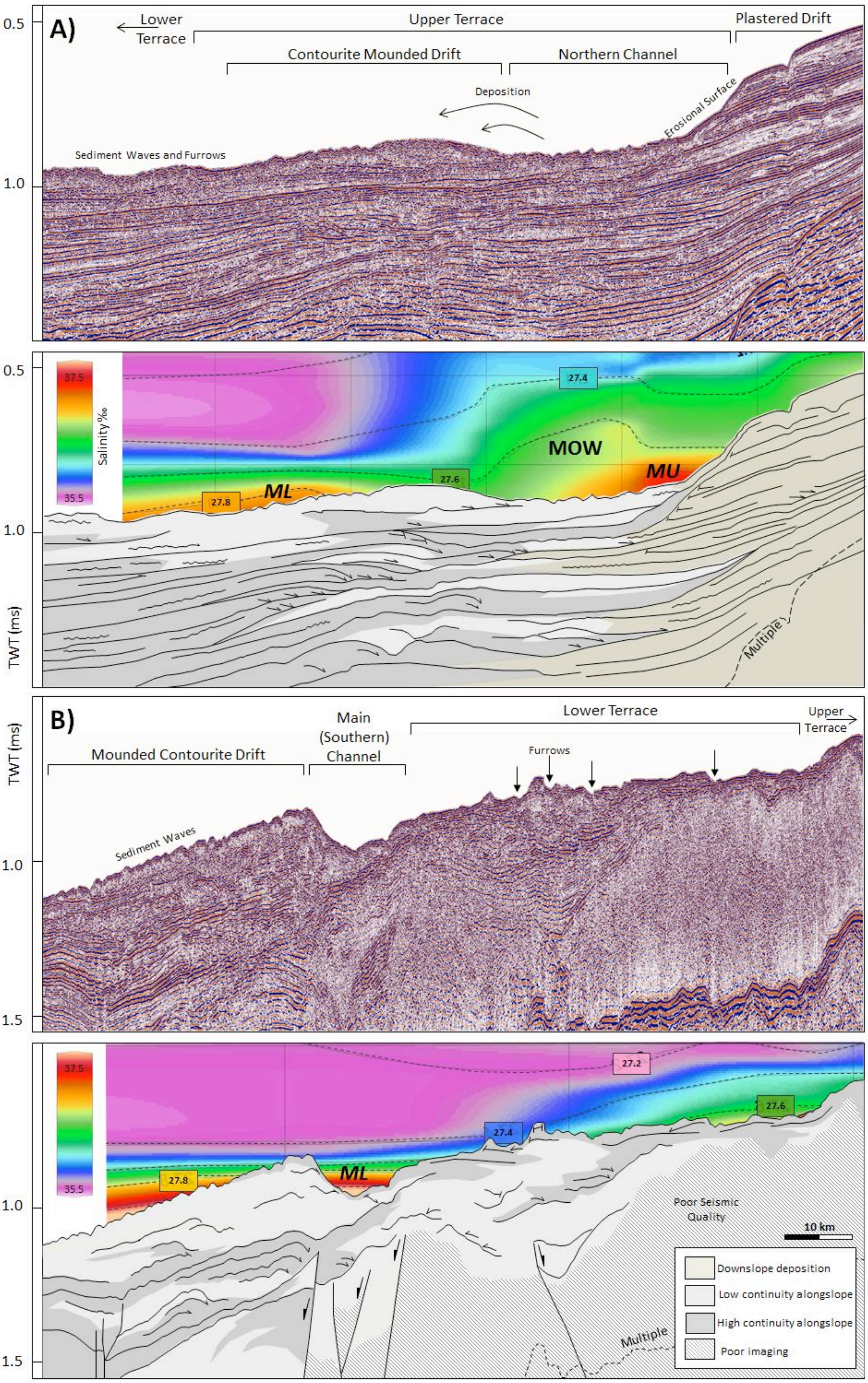


Figure 4.3: Seismic examples from the eastern Gulf of Cadiz. Oceanographic data from Schlitzer (2013). For locations see Fig. 4.1.

4.2.1 Identified Seismic Units

Six key seismic horizons have been picked across the area (Fig. 4.4), in addition to the acoustic basement and sea bed. These horizons separate seismic sequences that demonstrate different acoustic characteristics, and here they will be described. Isochron maps give clues to past MOW pathways by highlighting areas of erosion, versus areas of sheeted or mounded deposition. Based on industry borehole data, the depths and ages of the major Miocene and Pliocene discontinuities (Fig. 4.4) can be given with some confidence at a regional scale. The Quaternary succession has previously been carefully analysed (Llave et al., 2011) and care will be taken to note any comparisons and contrasts between the Quaternary and Pliocene successions.

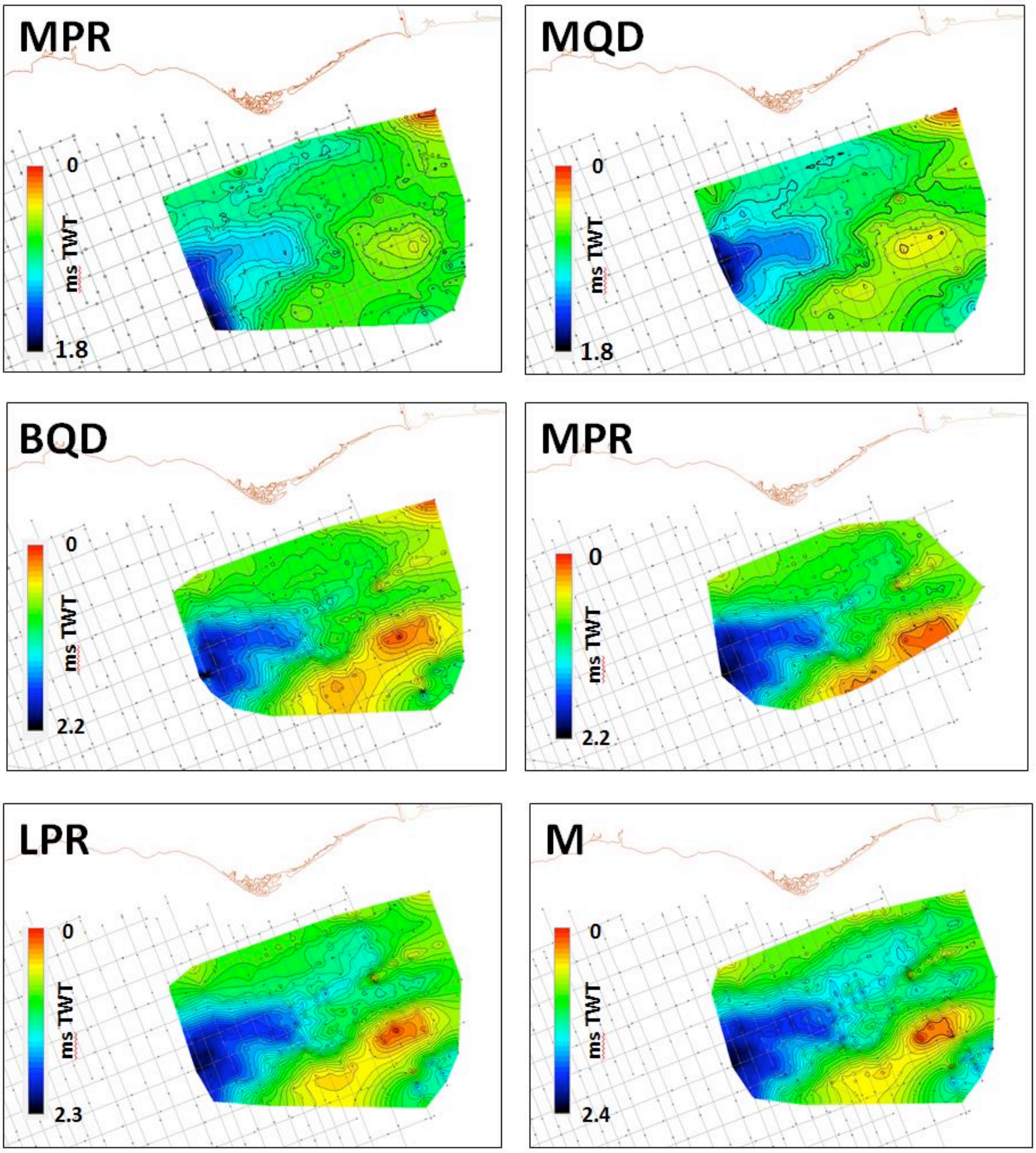


Figure 4.4: Depth to picked reflection (ms TWT).

4.2.1.1 Pre-Pliocene

A considerable thickness of older sediments underlay the Gulf of Cadiz contourite system. Maximum sediment thickness between the base Pliocene and top acoustic basement is 0.75 ms TWT, although the formation pinches out along many of the structural highs. The succession is heavily deformed, now observed as palaeorelief in the seismic data. Deposition of the Cadiz Allochthonous Unit (Medialdea et al. 2004) throughout the Miocene resulted in a complex array of depositional basins and tectonic highs. Neotectonism has since punctured the sediments in some regions, most notably in the east of the study area (Fernandez-Puga et al. 2007).

4.2.1.2 Seismic Unit P1

Bounding reflections: The basal reflection of seismic unit P1 is defined by a marked change in seismofacies and forms a major onlap surface (Fig. 4.5). It has been dated to the latest Miocene at ~5.3 Ma (Llave et al. 2011) and approximately marks the Miocene-Pliocene boundary. It has been named previously as Discontinuity M (Llave et al. 2010; 2011) and it should be noted that this differs in age from the Discontinuity M defined by Roque at al. (2012), which instead marks the *base* of the Miocene. The overlying seismic unit is here named P1 to correlate to the Llave et al. (2011) classification scheme and correlates, in part, to U1 in the Roque et al. (2012) sequence classification. The unit is tentatively dated as the Early Zanclean.

Distribution: Fig. 4.6 shows an isochron map of seismic unit P1 and clearly shows a considerable depocentre in the NE of the study area. Here, it reaches thicknesses of 0.25 ms but pinches out basinwards to the south and southwest.

Seismic character and evolution across the study area: Seismic unit P1 is made up of stacked high amplitude, laterally continuous reflection events. Locally, moderate reflection amplitudes appear at the base of this unit. In general, a weak response is observed at the base, increasing upwards and evolving towards high amplitude, laterally extensive reflections that top the sequence. This is in contrast to the underlying weak to semi-transparent and more chaotic seismofacies of the Late Miocene. The package has been deformed by Tertiary tectonics and to the north it is onlapping onto the palaeoslope relief and in places onto tectonic highs (Fig. 4.5). Deformation includes faulting, displacement due to the uplift of the Guadalquivir Bank and localised deformation by halokinesis (Fig. 4.5).

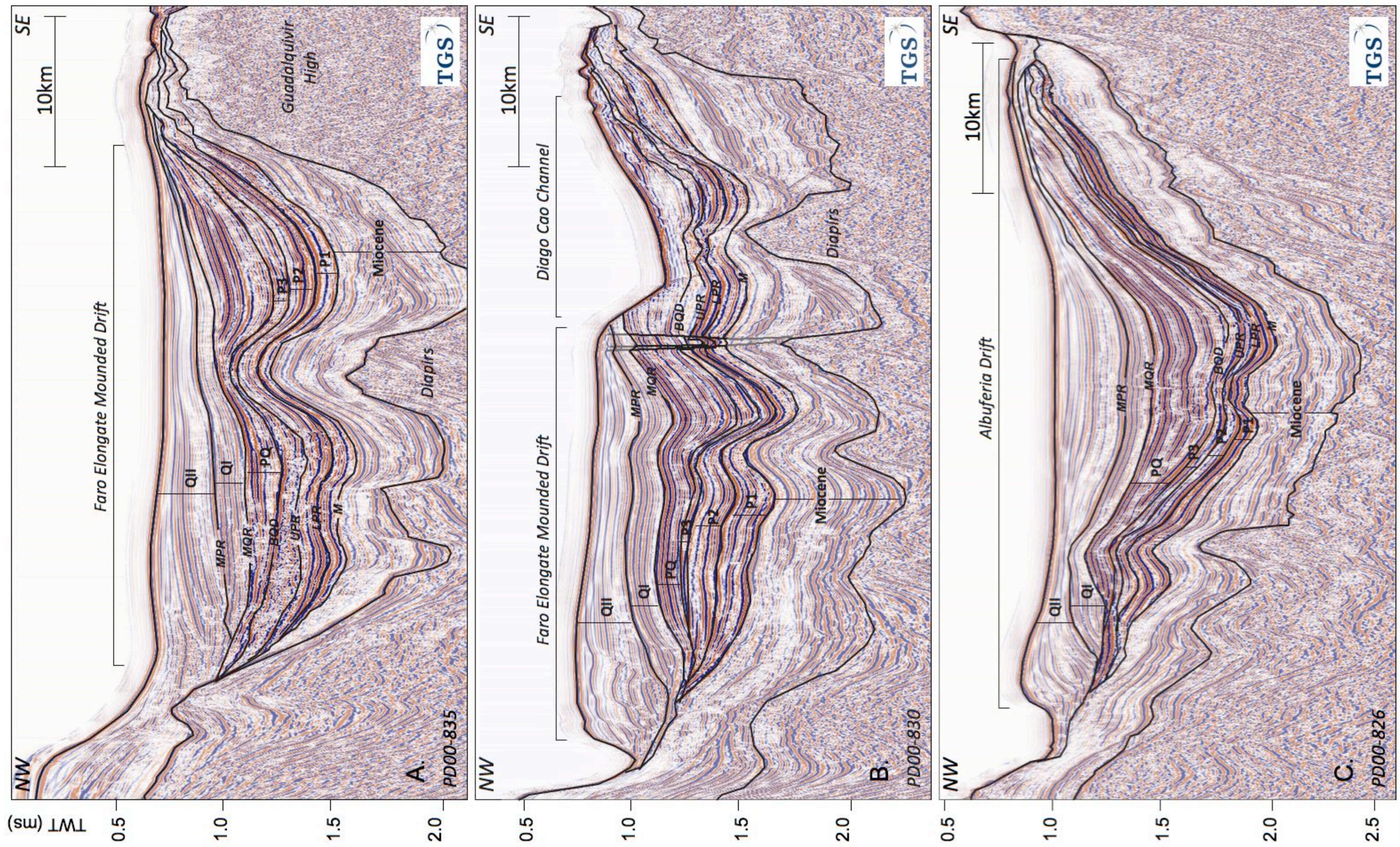
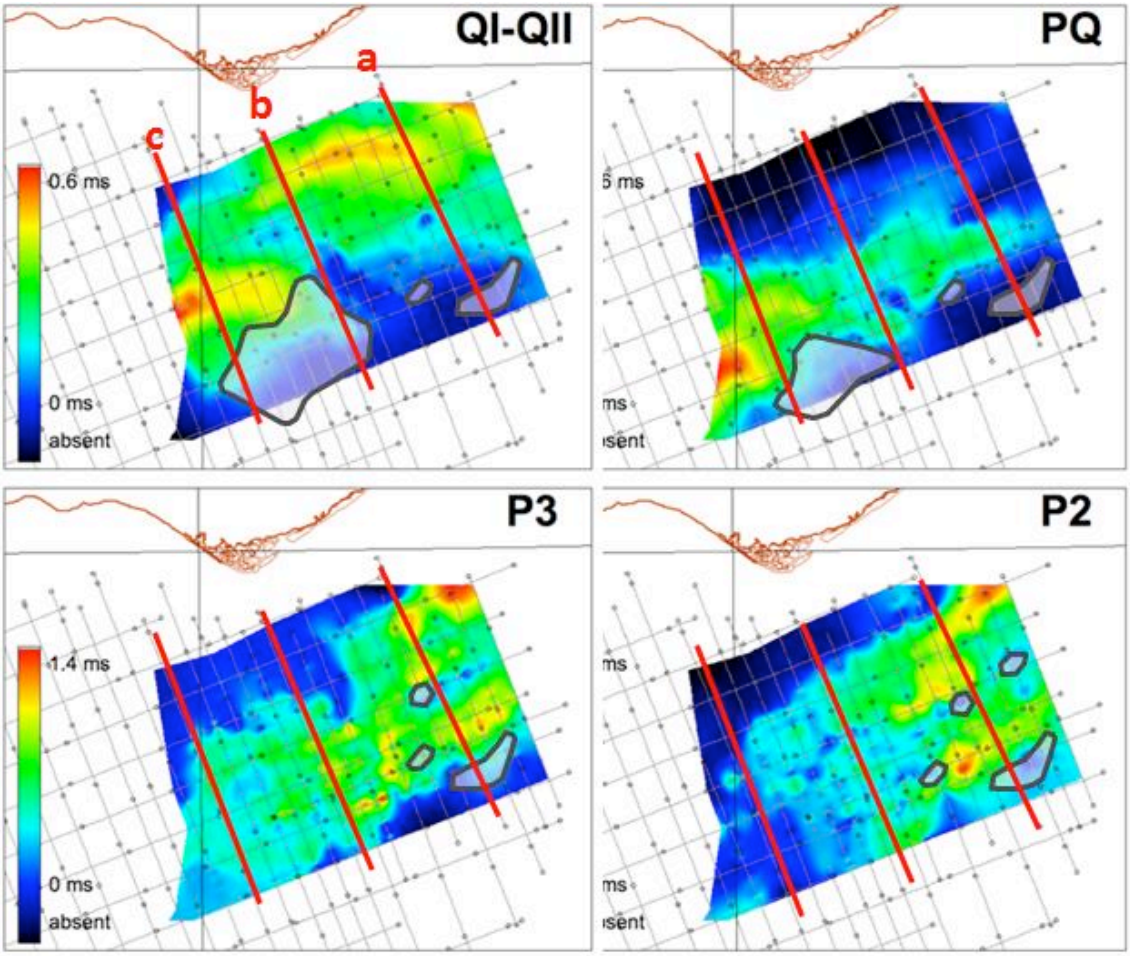


Figure 4.5: Seismic lines PD00-835 (A), PD00-830 (B) and PD00-826 (C). Locations indicated on Fig. 3.3 as red dashed lines. Seismic sequences are labelled and the key discontinuities named. MPR=Mid Pleistocene Reflection; MQR=Mid Quaternary Reflection; BQD = Base Quaternary Discontinuity; UPR = Upper Pliocene Reflector; LPR = Lower Pliocene Reflector; M=Top Miocene Discontinuity. Depositional sequences P1 – QII relate to those outlined in Fig. 3.4.



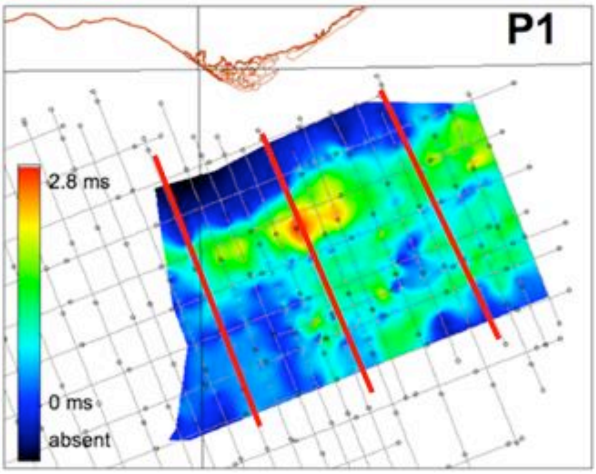


Figure 4.6: Isochron maps for depositional sequences P1-QII. Reds are depocentres. Structural highs are outlined in black. A clear contrast in the focus of deposition between the Quaternary and the Pliocene sections is seen. A major region or absent sedimentation (erosion) is seen in PQ.

4.2.1.3 Seismic Unit P2

Bounding reflections: Although largely conformable with the underlying P1 seismic package, the reflection separating units P1 and P2 is locally marked as an onlap surface (Fig. 4.5). In compliance with Llave et al. (2011), it is named the Lower Pliocene Discontinuity (LPR). Onlap is seen primarily along the continental slope, and to some extent in minor depocentres formed between the salt and mud diapirs. There appears to be localised upslope progradation along the continental slope in contrast to the onlap observed in the underlying P1 sequence.

Distribution: P2 reaches its maximum thickness in the northeast of the study area, where it is 0.15 ms TWT. Maximum thicknesses coincide with an area of chaotic seismic facies (Fig. 4.5 A). There is also a depocentre in the southeast reaching 0.13 ms TWT (Fig. 4.6). Towards the west, the package thins considerably and in places it is completely absent where it has been cut by later erosional surfaces.

Seismic character and evolution across the study area: In the east of the study area, there is a marked change in seismofacies across the LPR discontinuity. There is a change from laterally continuous reflections in seismic unit P1 to highly chaotic in P2. The package itself shows varied character across the region. To the northeast, a thick succession of chaotic seismic facies dominates (Fig. 4.5 A). However, basinwards and westwards alongslope, this evolves towards high amplitude, parallel reflections (Fig. 4.5 B).

4.2.1.4 Seismic Unit P3

Bounding reflections: The high amplitude reflections of seismic package P2 make way for more transparent facies over large swaths of the study area in P3 (Fig. 4.5 A). The thin (no greater than 1.1 ms TWT) Upper Pliocene P3 package is bounded by the discontinuities defined by Llave et al. (2011); the UPR at its base and the Base Quaternary Discontinuity (BQD) on top. The basal discontinuity is marked by a change in seismofacies in the southeast of the study area and localised onlap and downlap. There is some evidence that this is an erosional discontinuity (Fig. 4.5), and Llave et al. (2001) have noted its erosive character in other studies. The overlying sequence P3 is most likely Late Pliocene (Early Picenzian) in age.

Distribution: Seismic Unit P3 is completely absent across much of the north of the study area. Basinwards, it has been preserved, although significant thinning is seen over the diapiric ridges in the east. Elsewhere a consistent thickness of approximately 0.1 ms TWT is maintained with some thinning to the west (Fig. 4.6).

Seismic character and evolution across the study area: Seismic unit P3 marks a change in acoustic response, with a move to a weak semi-transparent seismic response throughout the study area. As with the underlying seismic unit P2, chaotic seismofacies characterise the northeast of the study area whereas semi-continuous, parallel reflections are seen in the remaining region.

4.2.1.5 Seismic Unit PQ

Bounding reflections: The Base Quaternary Discontinuity (BQD) is defined by previous studies (Llave et al. 2010; 2011; Roque et al. 2012) and is easily identified by its high amplitude. It marks the base of seismic unit PQ and the onset of seismic unit progradational stacking. Previous studies have dated this reflection as 2.6 Ma (Llave et al. 2011; Roque et al. 2012). The upper boundary is as yet unnamed and is identifiable due to its highly erosive nature in the east of the study area where spectacular erosional truncations are seen (Fig. 4.5 A). In this study, the erosional surface has been named the Mid-Quaternary Discontinuity (MQR).

Distribution: The seismic unit has been heavily eroded in the north of the study area and in places it is completely absent along the slope. Basinwards, the seismic unit is preserved and is seen to thicken considerably to the west (Fig. 4.6), which is in stark contrast to the underlying Pliocene seismic unit P3, which *thinned* to the west. Significant thinning over diapirs in the east of the study area is seen throughout the entire section.

Seismic character and evolution across the study area: A partially 'missing sequence' is identified across the upper slope, and as a result, the unit can only be seen in the south of the study area. Very little can be said about the original external geometry of the deposits, but up to four regional truncation and onlap surfaces have been identified within the section. High amplitude, laterally extensive aggradational seismic reflections with many reflection truncations are seen within the sequence (Fig. 4.5).

4.2.1.6 Quaternary

The Quaternary to recent section is marked by numerous reflection truncation and onlap surfaces. Seismic sequences are progradational and aggradational and show a clear progradation in an upslope direction. Two main depocentres are identified; one in the northeast, and one in the southwest of the study area (Fig. 4.6). The Quaternary section is the first sequence where erosional features have been preserved, and channels can be seen. The stacked sequences are highly complex, and outside the scope of the presented work. They have been examined in detail by Llave et al. (2001; 2007c).

Results

Chapter 4: Seismic Results

Chapter 5: Sedimentary Results

5 Sedimentary Analysis

5.1 Sediment Facies

An important aspect of contourite identification at core-scale is the facies and facies associations observed. This can be combined with more detailed sedimentological work to aid identification. Core sampling and detailed sedimentological analysis is, however, costly and un-attainable in many situations. In this section therefore, we examine the facies and their associations with the aim of 1) identifying any diagnostic criteria for contourite sands, and 2) consider the driving factors for the variety of sequences observed.

This work makes use of over 60 metres of sediment core from the sand-prone eastern Gulf of Cadiz from a variety of contourite depositional environments. These are: 1) three complete piston and one box core, with core top samples from a further four box cores collected from the eastern Gulf of Cadiz on the CONTOURIBER-1 scientific cruise; 2) three conventional cores drilled throughout the wider Gulf of Cadiz region during the IODP 339 Expedition; and 3) six lower- to mid-slope piston cores collected on the NERC Discovery cruise D249 (Fig. 3.1).

The above outlined cores represent a wide variety of sand-prone contourite depositional environments and processes so that a robust diagnostic criteria can be applied across the entire system. They also provide new data on the distribution of sand across the Gulf of Cadiz both in the past and today.

5.1.1 Modern Sand Distribution

The new data acquired over the course of this research expands our understanding of the modern day sand distribution on the sea floor. This work adds to that of Nelson et al. (1993) and Rogerson et al. (2011) to give a new and more complete map of sand distribution in the eastern Gulf of Cadiz (Fig. 5.1). The results of the analysis were proofed against an existing map of sand distribution as constructed by Nelson et al. (1993). This map covers mainly the northern part of the Gulf of Cadiz, and so can now be extended to the east using the new sedimentological data, and the new bathymetric data acquired on CONTOURIBER-1 (see chapter 4).

All the results have been gathered and the grain size distribution simplified in order to focus on the *sand* distribution. Table 5.1 lists the percentage of sand for each core top measurement and visually indicates the gravel, sand and mud (silt plus clay) portions. These have then been summarised on the map shown in Fig. 5.1.

This analysis gives a new and better understanding of the modern day sand distribution in the most sand-prone regions of the Gulf of Cadiz. The modern sand distribution shows a complex relationship between the MOW, sea floor morphology and sediment supply which will discussed further in Chapters 6-9.

5.1.2 Sediment Facies

A total of 13 cores have been logged, seven of which to a high level of detail. Care was taken to note facies and facies sequences throughout the visual logging process and sedimentary units were identified. Where applicable, the CT-imaging also aided logging and the additional information gleaned from the three-dimensional CT-images is outlined below.

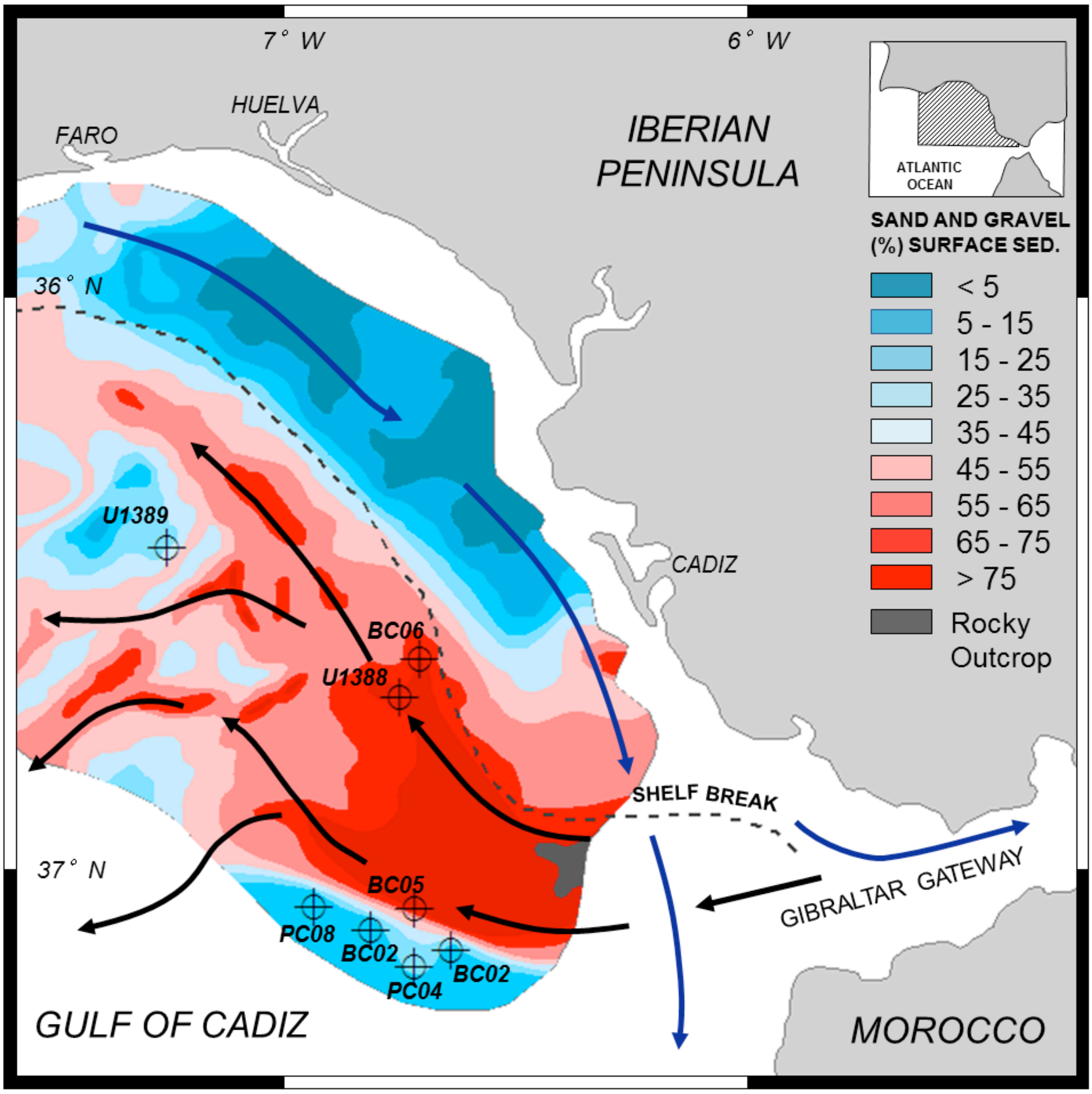


Figure 5.1: Modern day sand distribution across the Gulf of Cadiz. Modified from Nelson et al. (1993) using newly-acquired core-top grain size measurements.

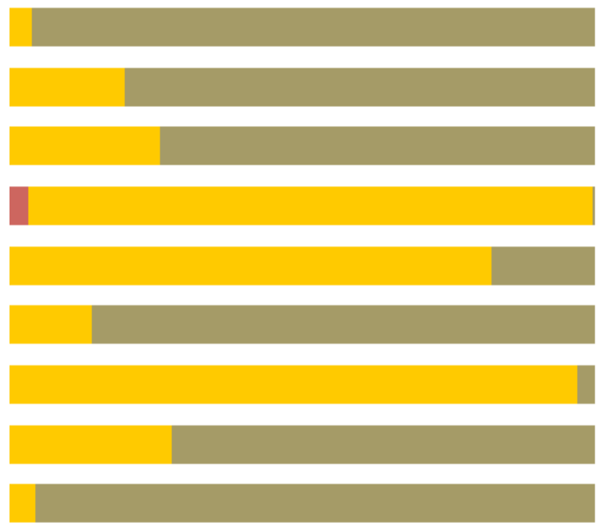
Cruise	Core	% Sand	0 % % GRAVEL: % SAND: % MUD: 100 %
CONTOURIBER	BC02	4.3	
CONTOURIBER	BC03	20.2	
CONTOURIBER	PC04 TG	26.1	
CONTOURIBER	BC05	99.5	
CONTOURIBER	BC06	82.4	
CONTOURIBER	PC08 TG	14.5	
IODP 339	U1388	97	
IODP 339	U1389	28.1	
IODP 339	U1390	4.9	

Table 5.1: The modern day sand content of each core top in the Gulf of Cadiz.

5.1.2.1 CT Results

An overview of the three piston cores that were scanned (PC04, PC06 and PC08) shows that there are clear differences in the bulk density of the sediment at each core site. Figure 5.2 show the entire CT-scanned core using the 'Rainramp' colour bar with a contrast of 800 and a brightness of 1130 in order to optimise the density contrasts within the cores. Each image was taken at 20 mm depth from the slabbed surface of the core. There is a marked reduction in scan quality in the coarsest sandy sections of the cores due to high fluid content. PC06 shows the poorest quality, particularly in the upper section (Fig. 5.2). Nevertheless, the core photographs, seen to the left of the CT-image (Fig. 5.2) show that the level of observed detail that X-ray computed tomography can yield is truly impressive.

The observed density contrasts are useful in the identification of discontinuities. There are some classic examples of the ichnofacies *Glossifungites* (e.g. PC04 at 4.5m) (Fig. 5.2) which is defined as an erosional hiatus from which large-scale burrows penetrate deeply into the underlying substrate (MacEachern et al. 1992). Some discontinuities in the piston cores appear to have been partially homogenised due to bioturbation activity – but many are still clearly observed, particularly where coarser sands are underlying. Such discontinuities may be used to separate sedimentary units.

The high level of detail CT-scanning provides has been used to examine sedimentary structures within the sediment that are otherwise masked in the soft sediment core. Discrete beds are clearly seen in the scanned image of the topmost 20 cm of PC04 and PC08 (Fig. 5.2) that are otherwise poorly imaged in the core photograph. The uppermost section of PC06 has been greatly fluidised on acquisition and transportation due to the unconsolidated and coarse nature of the sediment. Therefore, original sedimentary features have not been preserved in the top 40 cm. Elsewhere, there are some questionable indications of laminations (Fig. 5.3) and cross-bedding but these are usually masked by extensive bioturbation.

The resolution of the acquired CT-images is insufficient for precise identification of all the trace fossils; for that micro CT-scanning would be required. However, some types, for example *Chondrites* are very recognisable where fine-scale networks of burrows are seen in muddy sediment (Fig. 5.3). In silt- and sand- dominated sediments, naming trace fossils in more uncertain. The horizontal nature, sand fill and scale of many of the burrows seen in silt- and sand-dominated sections suggests *Thalassinoides*, *Palaophycus* and *Planolites* trace fossils which are commonly associated with contourite sediments (Fig. 5.3). There is a good example of the spiralling burrow of *Zoophycos* (Fig. 5.3), and also rare examples of deep-reaching *Trichichus* or *Skolithos* burrows. A rarely

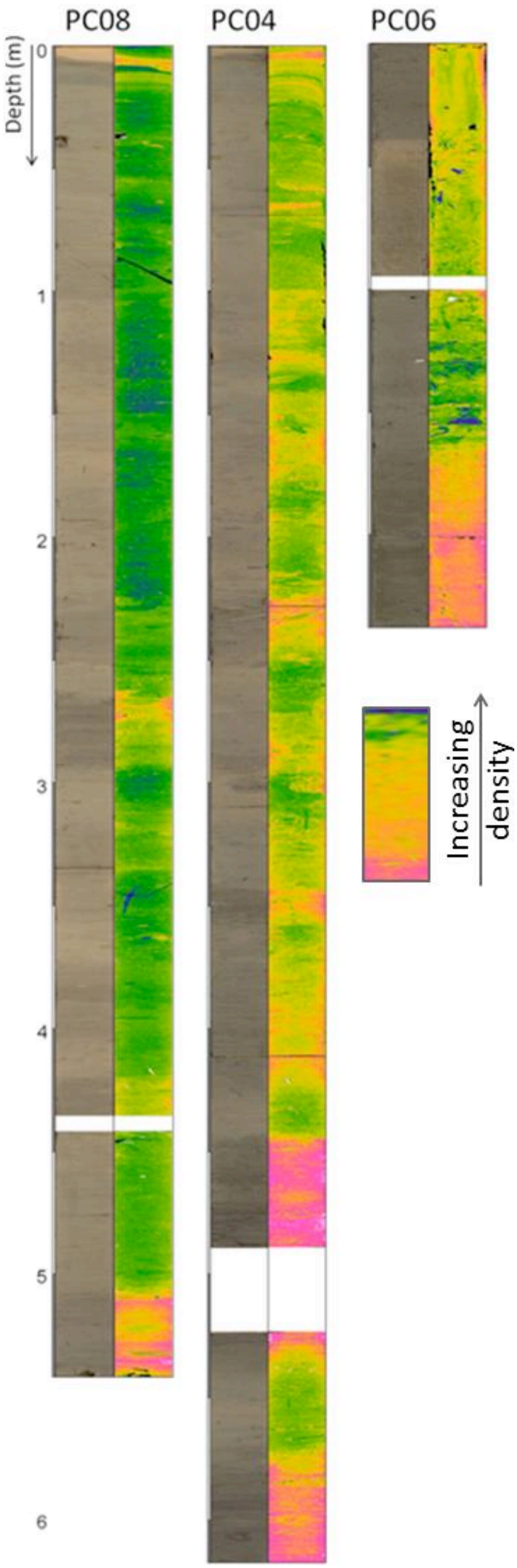


Figure 5.2: The three piston core photographs (left) with their accompanying CT scans (right).

preserved example of *Scolicia* is seen in PC04 at a depth of 5.5m.

5.1.2.2 Visual Logging Results

Visual logs were combined with CT-images to give logs of different resolution across the core sites. Seven cores were selected for detailed logging, and the upper six metres of each logged (where applicable) (Fig. 5.4). They were selected based on: 1) the availability of data – cores with additional data such as CT-scans and sediment samples were selected to give the most detailed of logs; 2) their position within the Gulf of Cadiz – key localities were selected from a variety of depositional environments to identify if there are any changes in facies across different contourite features; and 3) their sand content – this study targets sandier core localities in particular to aid characterisation of these facies. BC05 has also been assessed for facies in Figure 5.4, but logging was impossible due to the subsampling at acquisition. Many more cores were logged to a lesser resolution across the wider Gulf of Cadiz; the top ten metres were generally logged and can be seen in Figure 5.5. From the core logs, changing facies, discontinuities and tentative sedimentary units are identified.

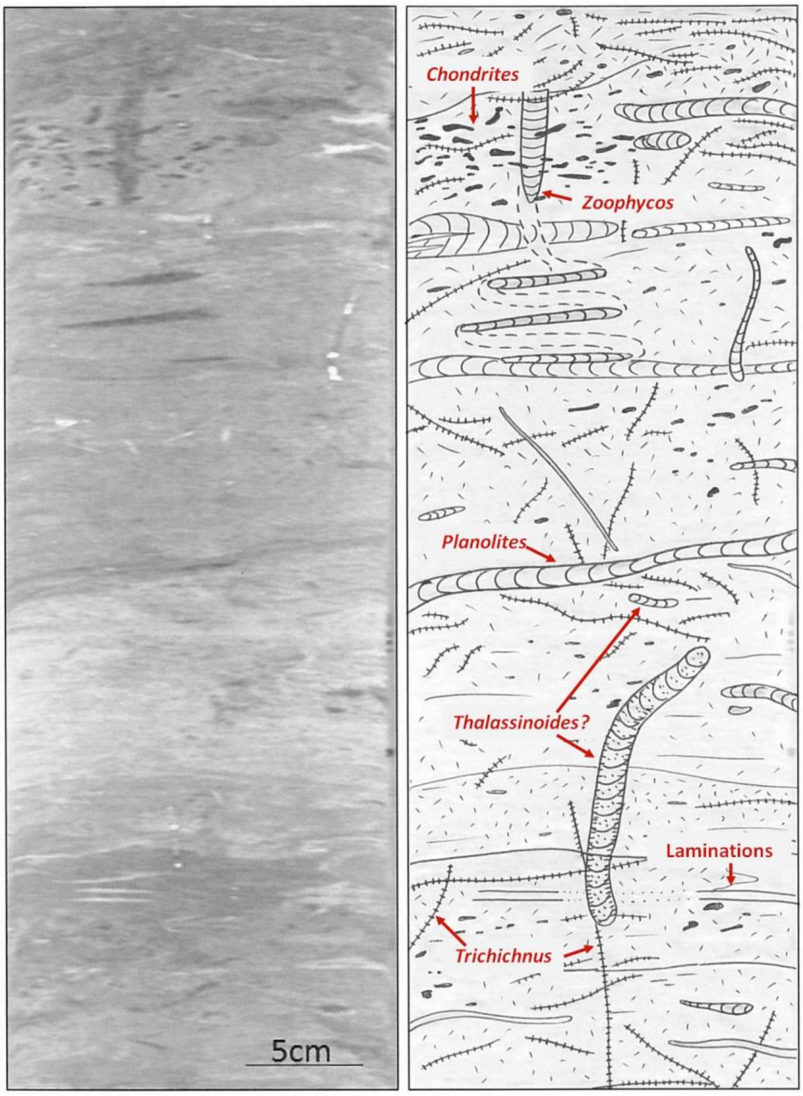
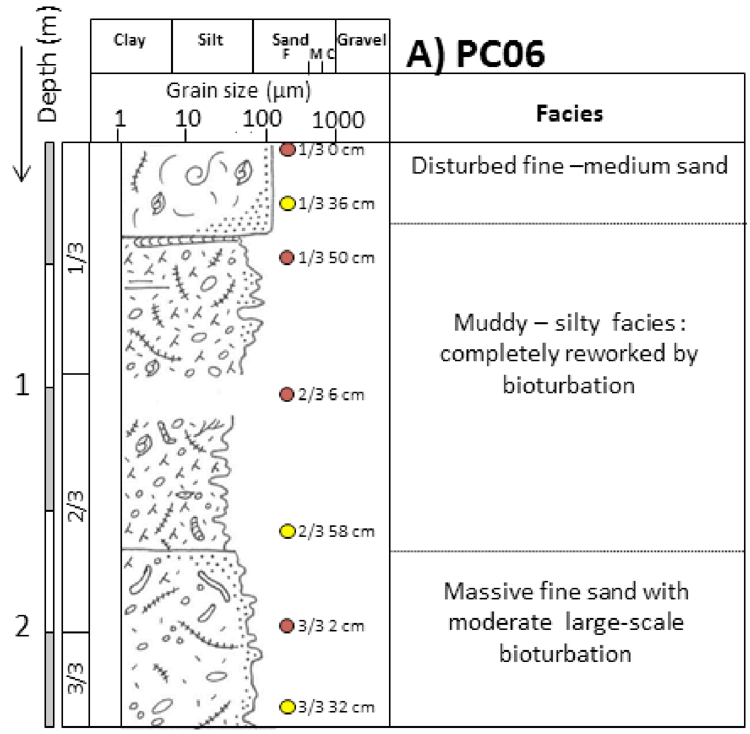


Figure 5.3: Example of the range of bioturbation styles in the piston cores. To the left is a grey-scale CT-scan of the core, and to the right the interpreted section. There is a particularly fine example of Zoophycos in this section. From PC04 3 m depth.



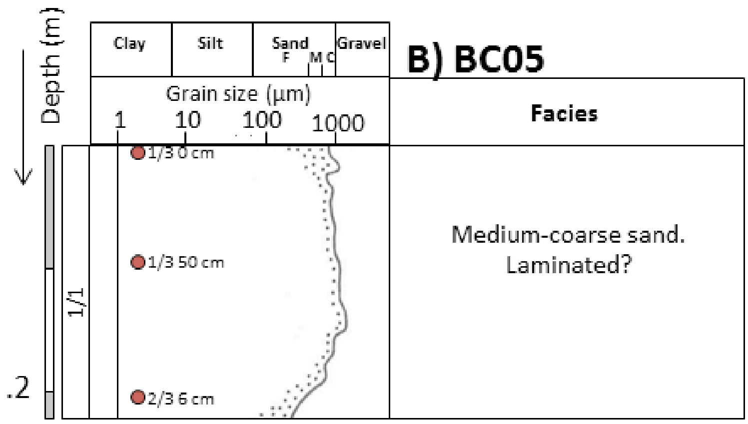
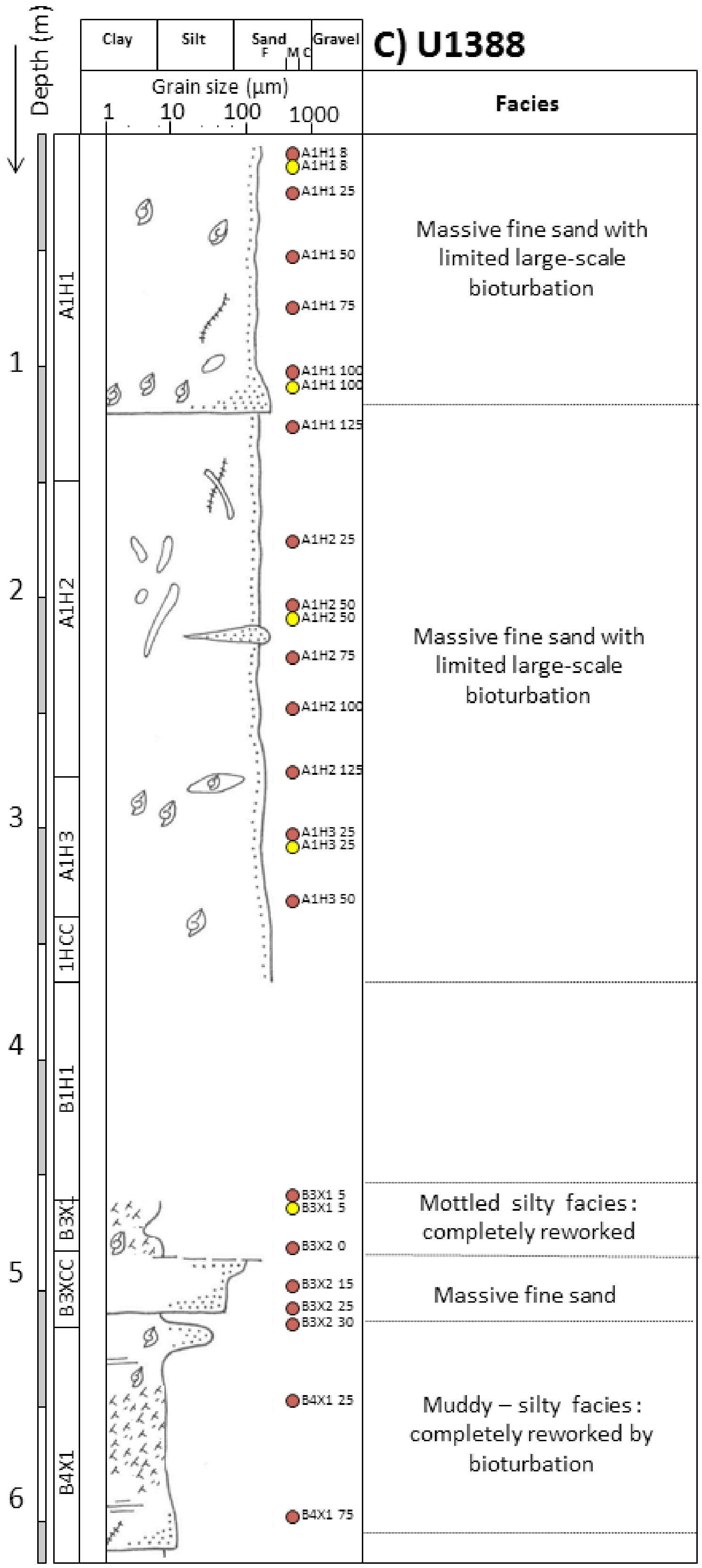


Figure 5.4 continued overleaf



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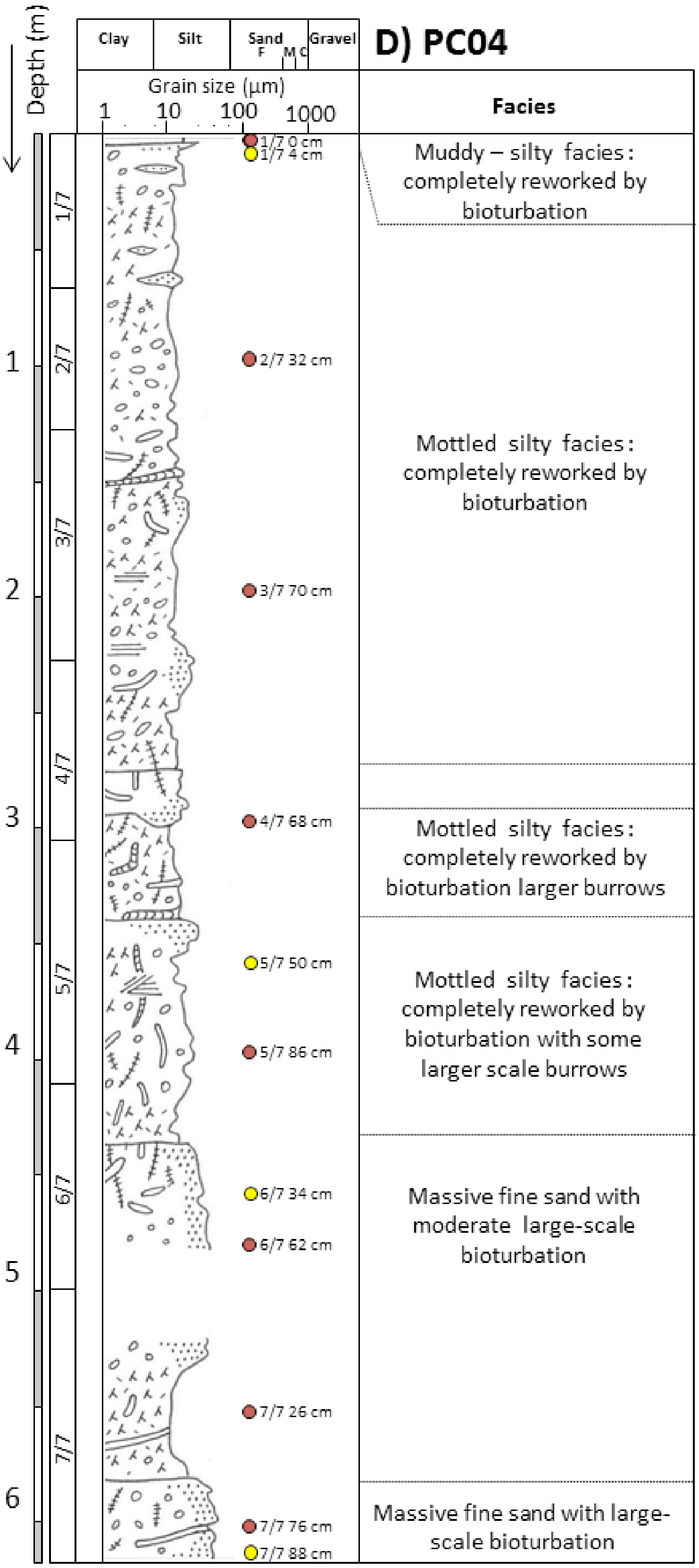

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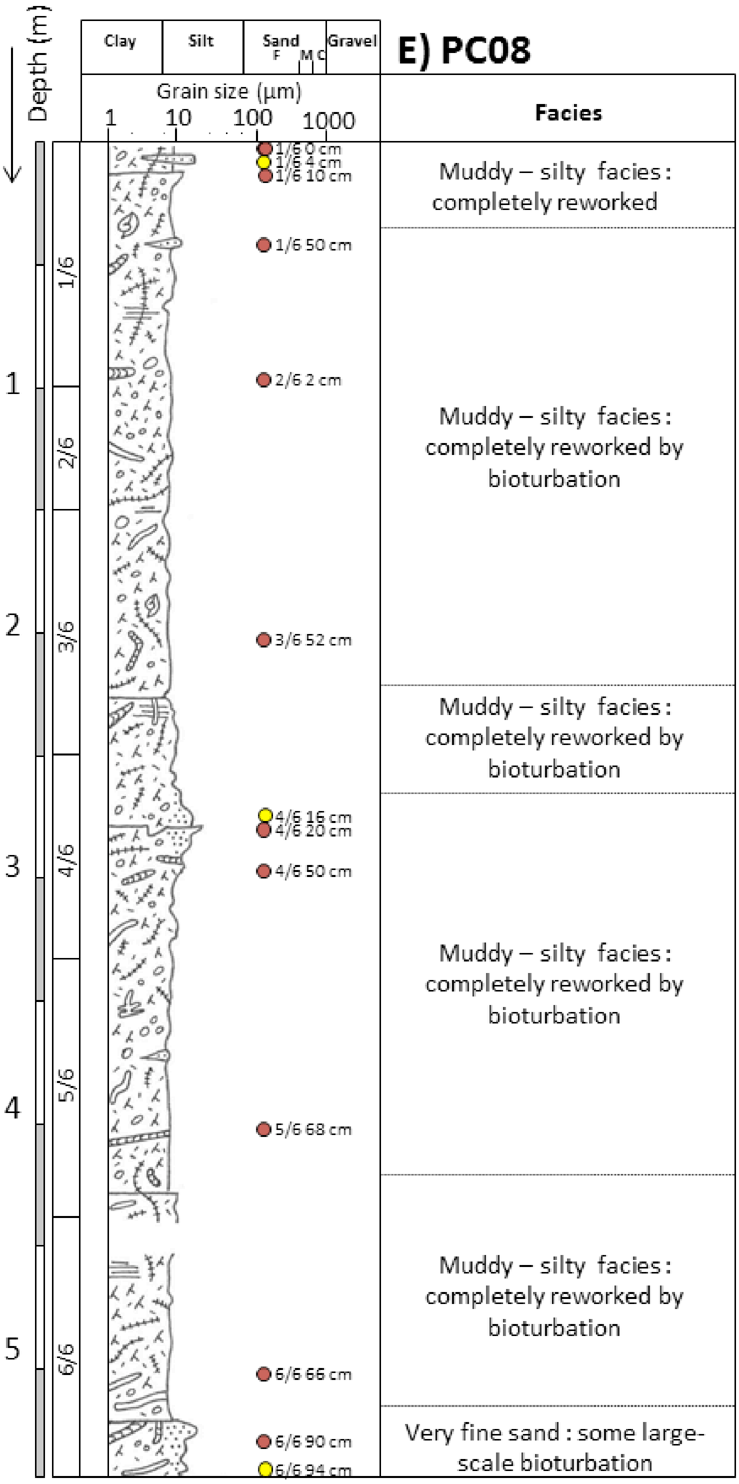

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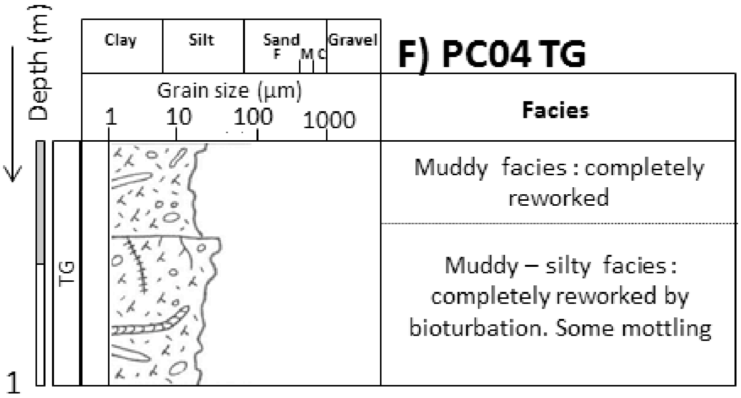
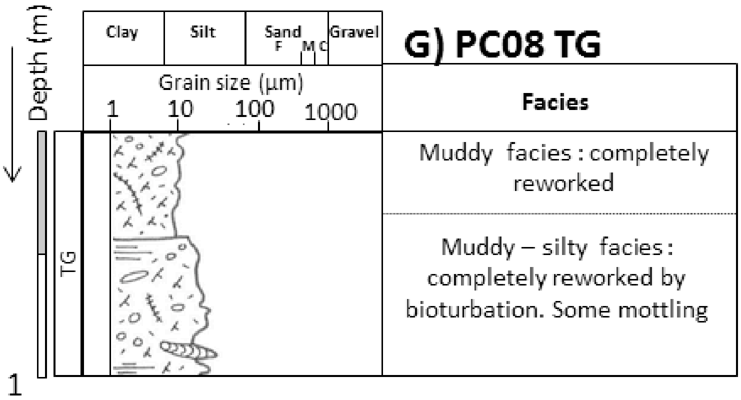




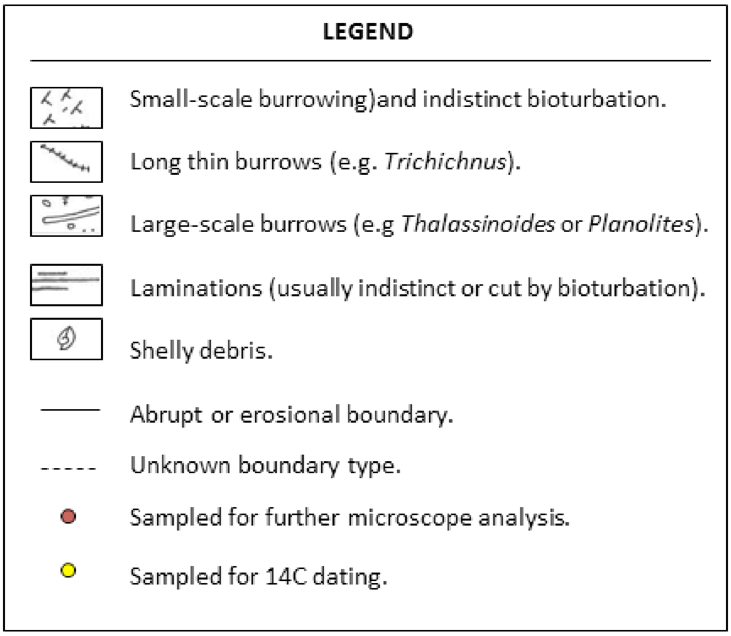


Figure 5.4 continued overleaf

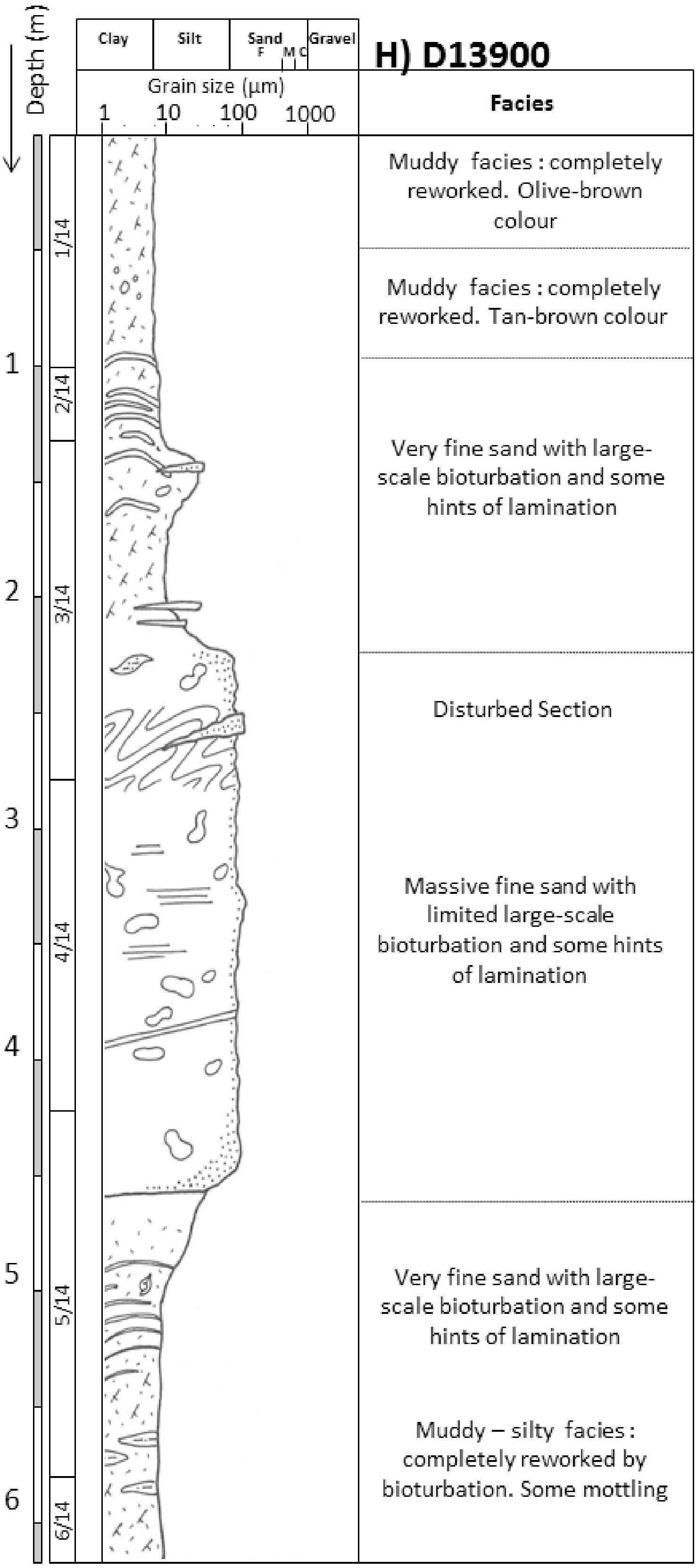


Figure 5.4: Detailed interpretation logs of eight of the gravity cores collected from the eastern Gulf of Cadiz. Facies description of the sediment are included. Core locations indicated on Figure 3.1.

Figure 5.5: Facies sequences observed across 12 sediment cores in the Gulf of Cadiz. Localities are indicated on Fig. 3.1. Vertical scale indicated on log U1386 (top left).

5.1.2.3 Contourite Facies

Within this sand-rich contourite depositional system, a number of distinct facies are identified and described below.

5.1.2.3.1 Bioturbated muddy contourite facies

Muddy sections regularly appear 100% reworked (Fig. 5.6 A). The core surface appears massive and structureless, with no bedforms seen to have been preserved in the CT-images. Very small-scale burrows can be distinguished in CT-images on the order of some millimetres

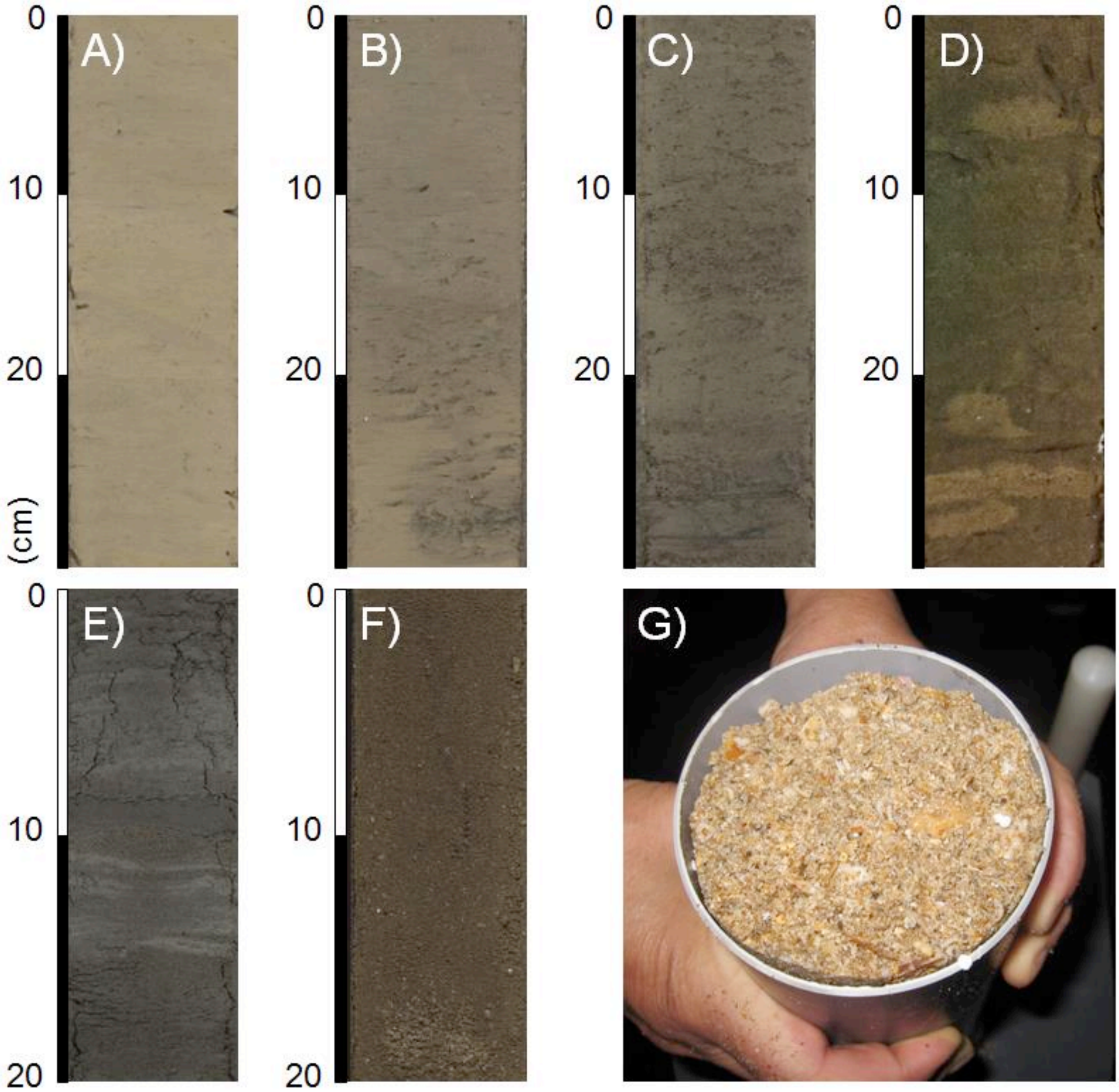


Figure 5.6: Contourite facies observed across the eastern Gulf of Cadiz. A) Bioturbated muddy contourite facies PC08_1 50-80 cm; B) Mottled silty contourite facies PC04_4 45-75 cm; C) Very fine sandy mottled contourite facies PC04_6 36-66 cm; D) Fine sandy bioturbated facies D13900_4 85-105; E) Medium sandy contourite facies with lamination U1388B_20X-5 68-78 cm; F) Massive medium sandy contourite facies U1388 A 1H-1 94-114 cm; G) Coarse sandy contourite lag sediment BC05 0 cm. Note changing vertical scales.

in length and are chaotically orientated and cross-cutting. Some thin but longer (2-10 cm in length) vertical burrows can be seen, particularly when a sand fill causes high density contrasts with surrounding mud. These are taken to be *Trichichnus* trace fossils (Fig. 5.3). *Chondrites*, a small-scale branching tunnel system, are also common (Fig. 5.3). Both these trace fossils are small-scale, showing diameters of only a few millimetres. Organic material and rare shell debris are also seen in the core. Contourite muds tend to be poorly sorted with a bimodal distribution (Stow and Faugères 2008) on account of a significant nannofossil and microfossil component, namely foraminifera (benthic and planktonic), and coccoliths. Bed thicknesses vary across the Gulf of Cadiz margin, but generally become thicker and more dominant towards the northwest and west laterally away from the main MOW core.

5.1.2.3.2 Mottled silty contourite facies

The silty facies found in the Gulf of Cadiz show characteristics similar to those seen in many contourite drifts. They occur as distinct beds, often grading into muds or fine sands, or they can form thin discrete layers and lenses within muddy facies. Highly bioturbated, fine silts often show a mottled appearance at the core surface (Fig. 5.6 B). As a result any sedimentary features are commonly partially or completely destroyed. Small-scale burrows are still common, but CT-imaging also shows examples of *Thalassinoides* and *Planolites* trace fossils that form spherical and elongate mud-filled burrows up to ten centimetres in length. These larger burrows are often subsequently cross-cut by other burrows such as *Trichichnus* (Figure 5.3). There are various large-scale (up to cm diametre) trace fossils that run horizontally across the sediment core which are interpreted as *Zoophycos* or sea bed ploughers *Scolocia* (Fu and Werner 2000). Where interbedded with muds or sandy facies, larger burrows can be observed clearly through visual logging due infill from overlying facies. The silts tend to be poorly- to very poorly-sorted.

5.1.2.3.3 Very fine mottled -fine bioturbated sandy contourite facies

Along with silty contourite facies, a large portion of the collected sediment core is made up of very fine and fine sandy material. Fine sands are found as discrete layers and lenses within other facies, or as thicker units. Very fine sands are commonly highly bioturbated, and can appear mottled as the silty facies do (Fig. 5.6 C), although they are more prone to discrete large-scale (up to 1 cm diameter) burrow preservation when compared to bioturbated silty facies (Fig. 5.6 D). Fine sandy facies are characterised by larger-scale burrows greater than a centimetre in diameter. *Thalassinoides* and *Planolites* form spherical and elongate mud-filled trace fossils up to ten centimetres in length. This bioturbation of varying scales is likely responsible for the range of sorting from very poorly- to moderate-sorting (Stow and Faugères 2008).

5.1.2.3.4 *Massive and laminated medium sandy contourite facies*

Medium and coarse sand facies are relatively rare, and often subject to poor core recovery rates. When they are successfully recovered, they are susceptible to becoming fluidised and deformed due to high water content. As a result, it is difficult to observe distinguishing features in these facies. Where preservation is better, CT-imaging aids the identification of features. Where the core reaches high sand content (greater than 70%) there is a marked reduction in bioturbation of the sediment. Very large-scale (greater than 1 cm diameter) burrows may be preserved (Fig. 5.6 D), with some rare hints of lamination (Fig. 5.6 E) Hernández-Molina et al. 2013b). Most commonly, however, medium sand facies are massive (Fig. 5.6 F). Coarser sandy and gravel lags and lenses are also common. They will tend to show gradational bed boundaries, grading to fine sand. There are also abrupt erosive contacts, particularly the upper boundary. Medium contourite sand facies tend to show poor- to moderately-sorting (Stow and Faugères 2008).

5.1.2.3.5 *Coarse sandy and gravel contourite facies*

Unconsolidated coarse sandy facies are notoriously difficult to collect without significant loss of material and deformation. Coarse sand facies are found most commonly in thin lag layers with erosive basal boundaries. Sub-sampling from box core BC05 (location shown in Fig. 3.1) shows gradational symmetrical grading and evidence of lamination. The coarse contourite sands have a large bioclastic component consisting of broken shelly material (Fig. 5.6 G).

The five facies above are seen in varying proportions across the study area. In addition, some other (non-contourite) facies are observed. Hemipelagics are homogenous and show distinct colour changes. Thin-bedded turbidites facies sequences show the characteristic sharp to erosional basal boundaries and fining upwards sequences (Fig. 5.5).

5.1.2.4 *Facies Sequences*

Compilations of logged fine-grained contourite facies from drifts around the world have led to the development of the widely recognised contourite sequences, first developed by Gonthier et al. (1984) and modified by Stow et al. (1986); Stow and Faugères (2008) (Fig. 5.7). The sediment cores used in this study were collected from a variety of different depositional environments across the eastern Gulf of Cadiz. Despite this, a set of repeating facies sequences are seen across the entire area (Fig. 5.5) showing the standard contourite sequence and variations (Gonthier et al. 1984; Stow and Faugères 2008). The following facies associations are seen: 1) The standard facies model consisting of facies divisions C1-C5 (Stow and Faugères 2008) (Fig. 5.7); 2) The standard model minus the mud-dominated C1 and C5 divisions; 3) Base-cut contourites consisting of C3-C5; 4) Top-cut contourites consisting of C1-C3; and 5) C3-only contourite sands (Fig. 5.7). Each sequence is described below.

5.1.2.4.1 Full contourite sequence

The standard bigradational contourite sequence (Fig. 5.7) consists of the full range of contourite facies from mud to sand (reverse grading), and back to mud (normal grading). This is termed bigradational grading. The Gulf of Cadiz cores show some excellent examples of the complete bigradational sequence for contourites with all the divisions from Stow and Faugères (2008) present. Grading is, in general, not symmetrical over the length of the core, and is most commonly skewed towards a top-cut-out contourite facies sequence. Good examples are seen in cores D13900, U1386 B 2H4, and U1389 (Fig. 5.4 H; Fig. 5.5). Other sequences that exclude the sandy C3 division are seen in D13896 (Fig. 5.5). These facies sequences are most prevalent in more distal (>150-200 km from the Gibraltar Gateway) core sites.

5.1.2.4.2 Divisions C2-C4

There are a number of observed facies sequences that are lacking in muddy facies. These result in contourite facies that are made up of divisions C2-C4 only. These are most commonly found in cores collected from channel localities that are in the order of 100 – 150 km from the Gibraltar Gateway. They are frequent in cores PC06 and U1388 (Fig. 5.5).

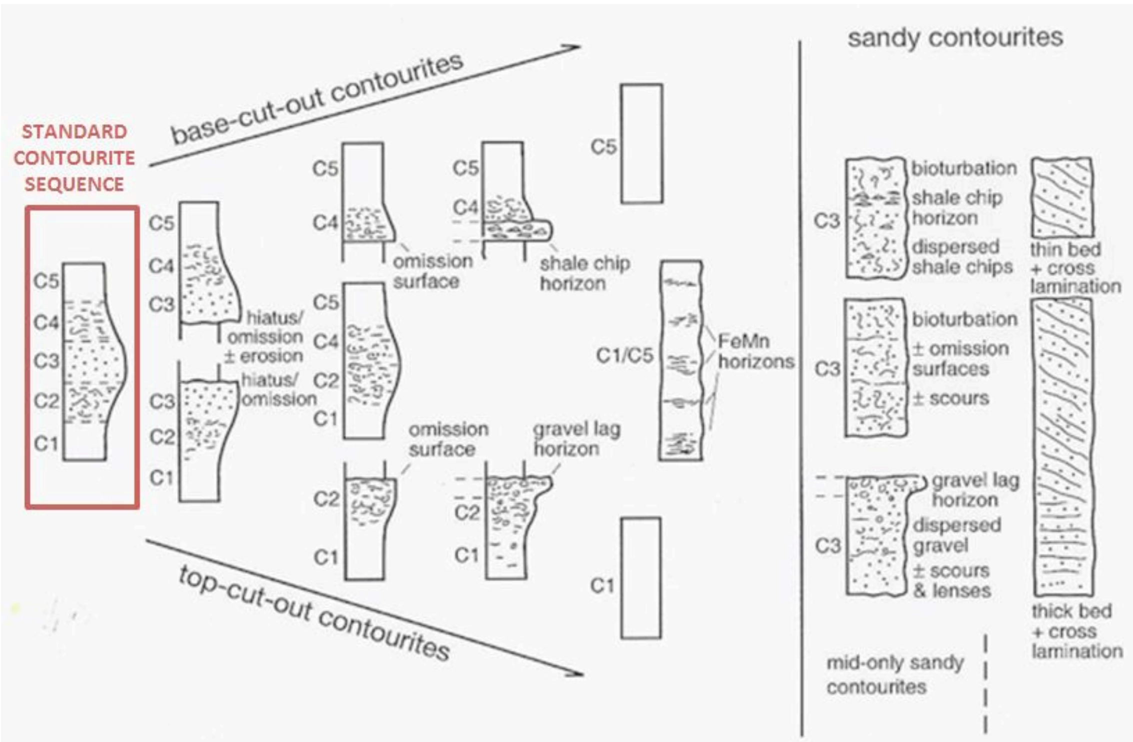


Figure 5.7: The standard recognised contourite facies sequence (boxed) from Gonthier et al. (1984) and modified by Stow et al. (1986); Stow and Faugères (2008)*. Possible variations to the standard contourite model are also shown. Modified from Stow et al. (2008).*

5.1.2.4.3 Base-cut contourites consisting of C3-C5

Base-cut-out contourites are essentially normally graded, and made up of divisions C3-C5. There are a number of these facies sequences seen in the recent sediment of the Gulf of Cadiz, for example in cores D13899 4/4, U1388 B 4X1, and U1389 B 1H4-5 (Fig. 5.5). From the base of the sequence, the abrupt or erosional boundary will separate the underlying finer-grained sediment from the overlying C3 division. The overlying sand- or silt- dominated sediment will generally be massive (structureless) and heavily bioturbated.

5.1.2.4.4 Top-cut contourites consisting of C1-C3

Some good examples of top-cut contourite facies sequences are seen in PC04, PC08 and D13075 (Fig. 5.5). They show reverse grading (divisions C1-C3) and are topped by an abrupt or erosional boundary. A detailed log of a top-cut contourite is seen in Fig. 5.8. It shows changing bioturbation patterns in each facies; muds are heavily bioturbated and small-scale burrows are evident throughout. There are some indications of partially destroyed laminations in the lower unit of Fig. 5.8. Moving up through the sequence to divisions C2 and C3, a more mottled appearance is seen with some larger (>1 cm diameter) burrows observed. In the case of the example shown in Fig. 5.8, the overlying sequence shows a thin section of normal grading at its base before resuming to a reverse grading trend. This overlying bottom-cut-out contourite sequence is common above top-cut-out contourite sequence examples (see also PC08 3m).

5.1.2.4.5 C3-only contourite sands

The cores reveal a number of sand-rich sequences that show no grading, but instead are massive and thick. These are made up of the C3 division of the contourite sequence model only. Core sites U1388 and PC06 show the best examples, with sand-dominated beds being bounded by erosional surfaces both to the top and bottom of the sequence (Fig. 5.5). Such facies are usually made up of medium to coarse sands and show little evidence of bioturbation (except for rare large (>1 cm diameter) burrows (Fig. 5.6 D). The main 'structures' to note are local coarse lags and lenses (Fig. 5.8 F). In some rare examples, laminated beds are locally observed (Fig. 5.6 E). For example, medium sands deposited in high energy contourites channels (as seen in U1388) are massive with erosional scour surfaces and local coarse lag lenses. Further coarsening leads to laminations. This is in contrast to finer contourite sands deposited on contourite drifts (e.g. PC04) which hint at some lamination, but are broadly bioturbated. Medium sand is also observed in core D13900 located on a fan drift at the end of a contourites channel and shows large-scale (>1 cm diameter) burrows throughout.

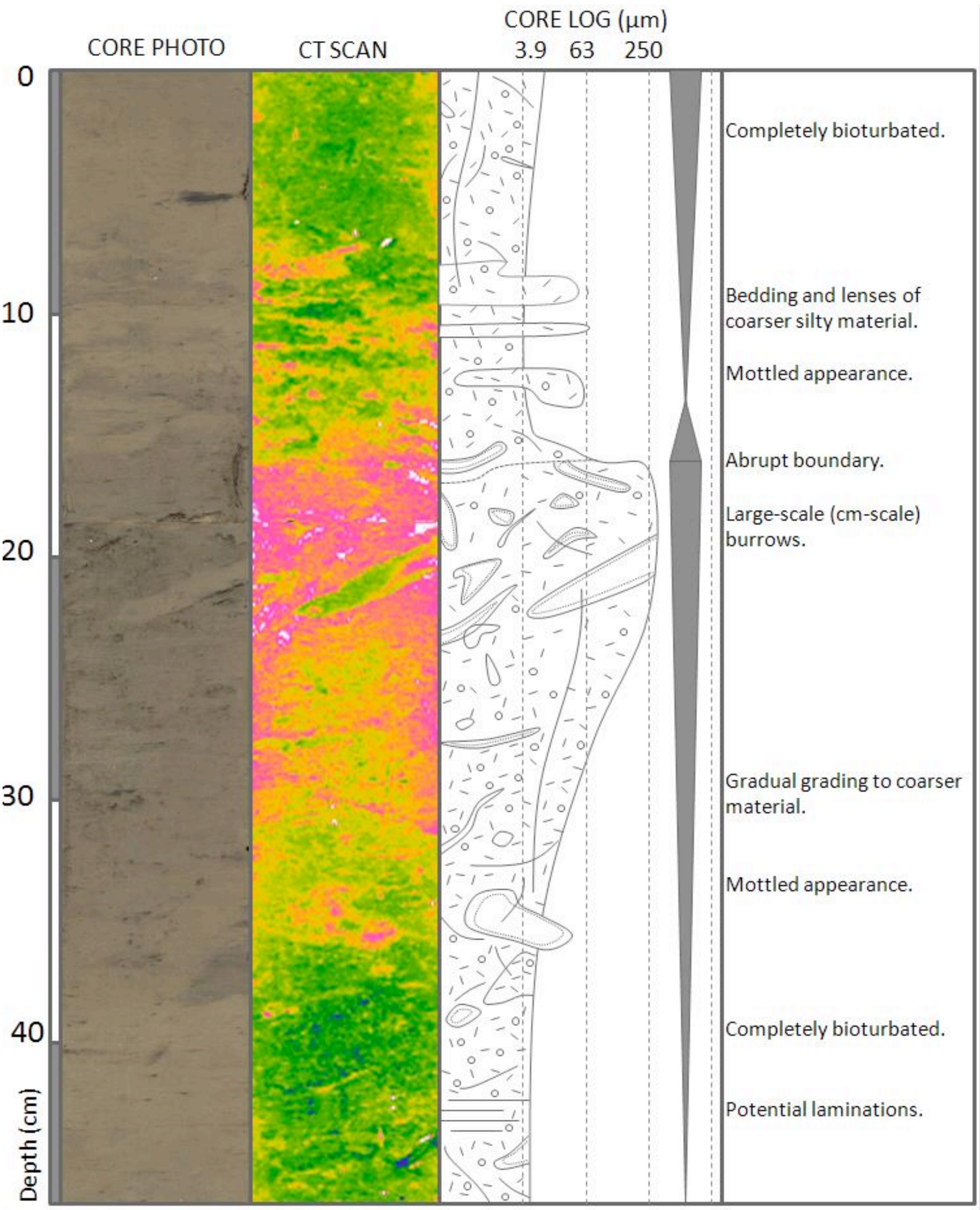


Figure 5.8: PC04 section 3/6 78-105 cm and section 4/6 0-34 cm. A detailed log of a typical sequence, and details of features observed. Gradational boundaries are observed, particularly between mud- and silt-dominated facies. Silt- to sand-dominated facies are separated by a relatively sharp boundary that does not appear to be erosive.

Examination of the sediment facies reveals that despite the Gulf of Cadiz contourites being very sand-rich, a wide variety of facies are observed. Key results are;

1) Bioturbated mud through to coarse sand facies are observed.

2) There are a number of different contourite sand facies that are tentatively thought to be related to a combination of sediment supply and depositional processes.
3) Top-cut- and base-cut-out sequences are common due to the high number of erosional surfaces in this high-energy system. The complete contourite sequence (C1-C5) is actually relatively rare but is mostly seen at core sites more distal (>200 km) from the Gibraltar Gateway.
4) Medium to coarse sand facies are restricted to contourite channel localities, where they may be laminated or massive. Mottled silts to bioturbated fine sand facies are more common on drifts
5) Every single core site shows considerable change in facies that implies that the MOW is highly variable over time and space.

The above work will be used to aid contourite sand characterisation at core scale and discuss any links between depositional processes and facies that can be used to further our understanding of the Gulf of Cadiz contourite sand depositional system.

5.2 Sediment Composition

Detailed sedimentological work has been carried out on three piston cores and one box core, located in the eastern Gulf of Cadiz, to characterise the varying depositional environments across the study area. Piston cores PC04, PC06, PC08, and one box core BC05 (Fig. 3.1) were collected on the Scientific Cruise CONTOURIBER-1. The cruise collected complementary remote sensing data including swath bathymetry, seismic and parasound that has been described previously in Chapter 4. Approximately 14 m of gravity core was collected. The box core was sub-cored and sliced at a resolution of 1 cm. From there, sub-samples were collected approximately 10 cc in volume.

5.2.1 XRF Results

In total, fifteen elements were counted, listed in Table 5.2 along with their importance. The raw XRF data, provided in excel spreadsheet format, is difficult to use to identify trends, therefore a number of key cross plots and curves (plotted against depth) have been made. The XRF output of element 'counts' is difficult to translate into an accurate reading of element concentration due to the heterogeneity of the core and the limited energy reading ranges. Therefore, ratios are generally used to show down-core changes and aid correlation between cores (Weltje and Tjallingii 2008).

5.2.1.1 Down-Core Trends

There are a number of elements that are particularly useful to plot for down-core trends. Elsewhere in the literature, the elemental portions of iron (Fe) and calcium (Ca) have been used with great success in the Atlantic Cenozoic sediments to represent changing trends in terrigenous input versus normal pelagic and hemipelagic settings, and this has been linked to glacial/interglacial cycles (Richter et al. 2006; Rogerson et al. 2011). Here, the Ca and Fe counts show some significant results (Fig. 5.9). It is seen that although two of the cores show a near-identical low or high Fe and Ca count responses with depth, PC08 shows a mirror image Ca and Fe count response (Fig. 5.9). The Ca/Fe signal for the three piston cores has also been plotted against depth (Fig. 5.10) and high variability is observed. The Ca/Fe signal from PC08 loosely resembles that of the expected Quaternary $\delta^{18}O$ signal (Schultz and Zeebe 2006). PC04 shows a more limited range of values indicating near consistent ratios of Ca/Fe down the core (Fig. 5.10). PC06, located in the upper slope, shows very different Ca/Fe values from the two cores downslope. Extremely high Ca/Fe count values are observed in the top metre of the core before a decline to those seen in PC04 and PC08 (Fig. 5.10).

Element		Atomic Weight	keV	Importance
Al	Aluminium	27	1.49	Clay Minerals
Si	Silicon	28	1.74	Siliciclastic minerals and nannofossil (e.g. diatoms)
P	Phosphorus	31	2.01	Nutrient influx indicator and River influx
S	Sulphur	32	2.31	Syngenetic and diagenetic pyrite
Cl	Chlorine			
Ar	Argon			
K	Potassium	39	3.31	Clay minerals / acidic (continental) igneous rock provenance
Ca	Calcium	40	3.69	Palaeoclimatic indicator
Ti	Titanium	48	4.51	Basaltic (oceanic crust) provenance
V	Vanadium			Indicator of anoxic conditions
Mn	Manganese			Bottom water oxygenation
Fe	Iron	56	6.40	Oxygenation
Rh	Rhodium			Core casing

Table 5.2: Elements counted and their importance (Weltje and Tjallingii 2008; Rõhl 2010; Shackley 2011).

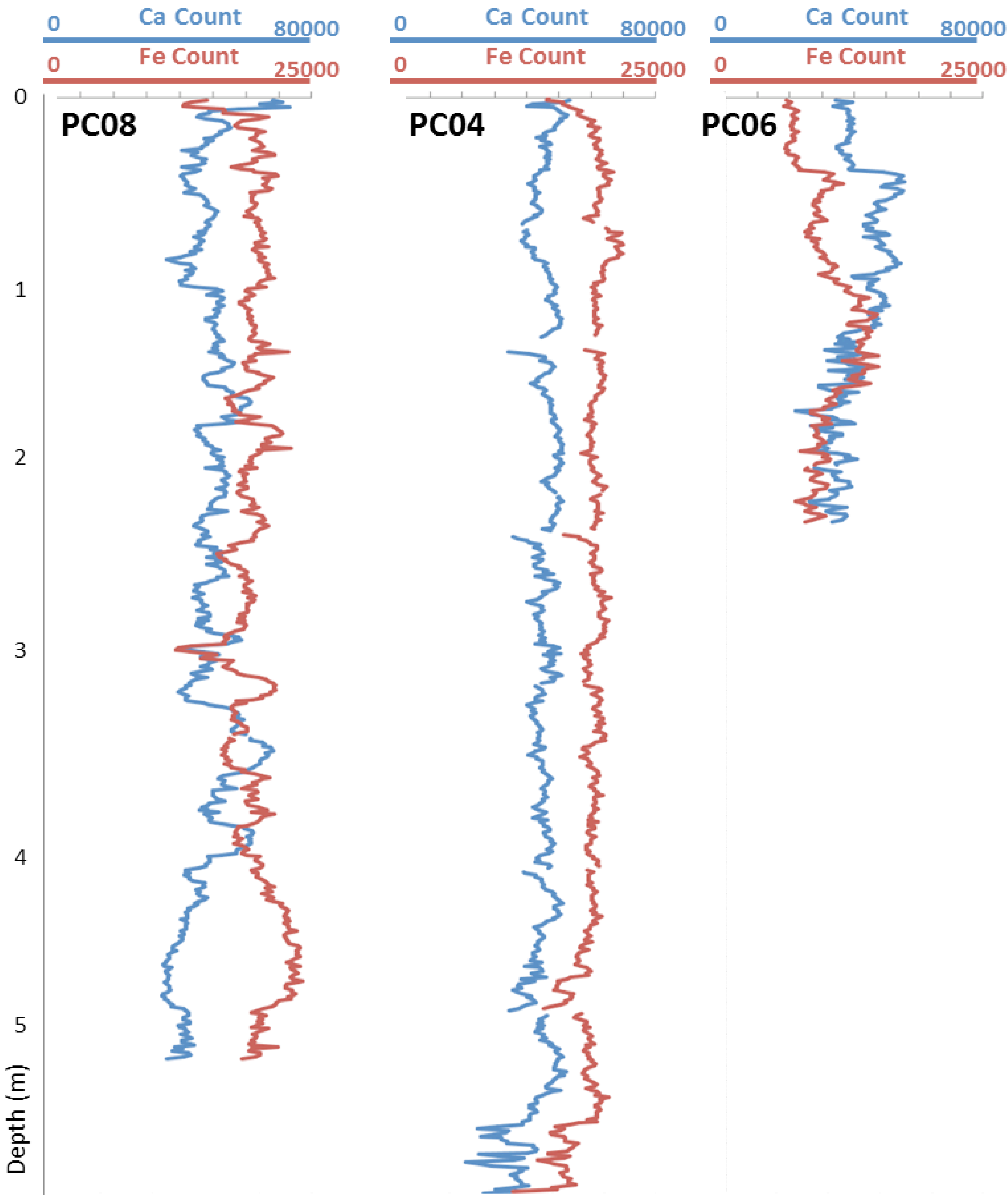


Figure 5.9: Plot of Ca and Fe counts against depth. PC08 is located in the deepest water depth and therefore plotted on the left, with cores shallowing to the right. PC08 shows opposite Ca and Fe trends, whereas PC04 and PC06 show similar trends.

Other elemental ratios have been plotted against depth where they have been found useful elsewhere in the literature. Some studies have shown that Mn peaks and other redox-sensitive elements in XRF measurements can be linked to palaeo-oxygenation of the sea floor (Janson et al. 1998; Richter et al. 2006). In other studies, low Mn count values are related to more anoxic bottom water conditions; whereas peaks indicate the region is swept by well oxygenated bottom waters. The Mn count signal must be calibrated against other redox-sensitive elements such as Fe (will show a corresponding high) and V (will show a relative low) in order to ensure the signal is not merely associated to provenance changes or digenetic processes (Yarincik et al. 2000). Figure 5.11 shows that Mn counts are often greater than 1.5 x 10^3 which are exceptionally high values. The signal also shows an extremely high level of cyclicity, and hence a moving average curve has been plotted to show longer-scale trends (Fig. 5.11). When compared to the Ca/Fe curves some interesting associations can be observed. In PC08 and PC04, Mn peaks are concurrent with Ca/Fe lows. The same can be seen in PC06, located upslope. However, the counts are significantly lower than those measured at PC04 and PC08. This may be due to acquisition discrepancies.

In addition, Wehausen and Brumsack (1999) uses coincident Si/Al, Ti/Al, Mg/Al, K/Al and Zr/Al peaks and relate to times of enhanced winnowing. In this study, Si, Ti and K have been plotted to assess for any trends and aid correlation across the cores (Fig. 5.12).

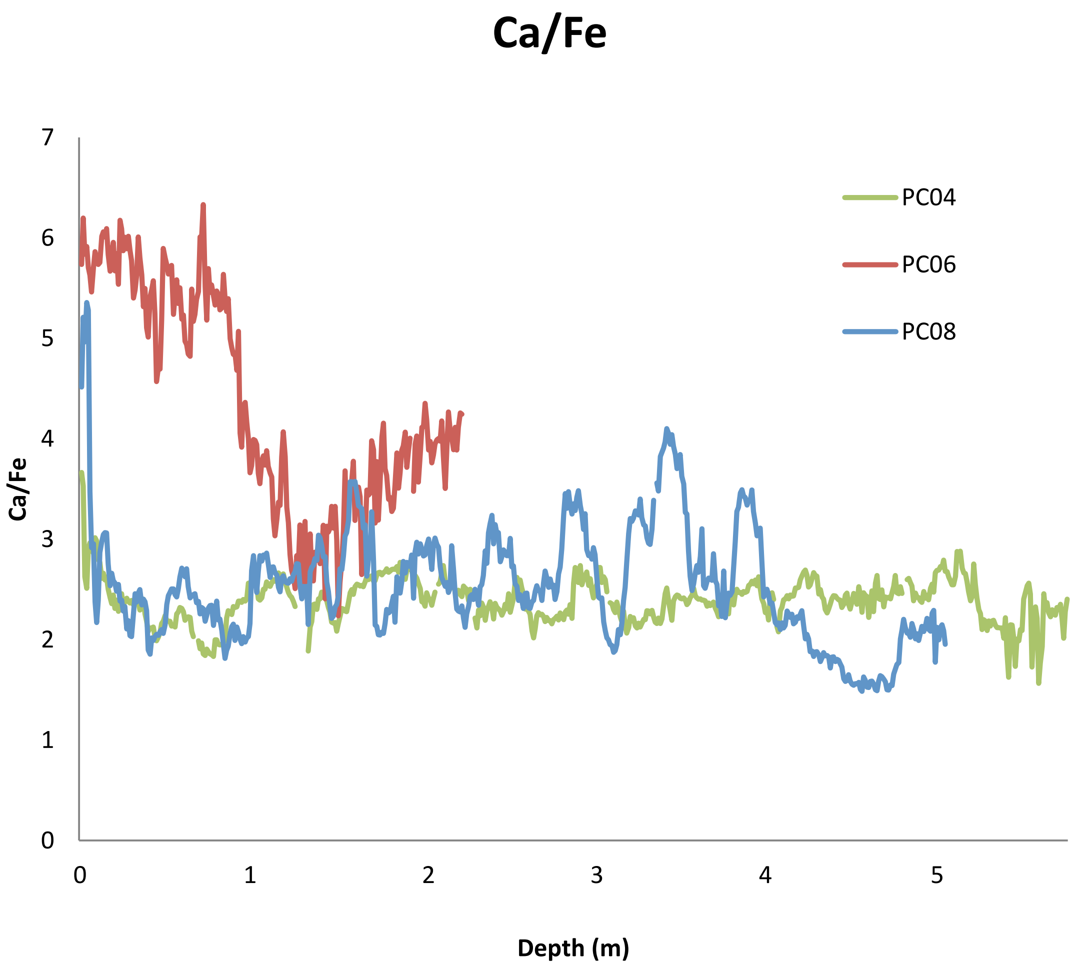


Figure 5.10: Ratio of Calcium (Ca) to Iron (Fe) for the piston cores plotted against core depth.

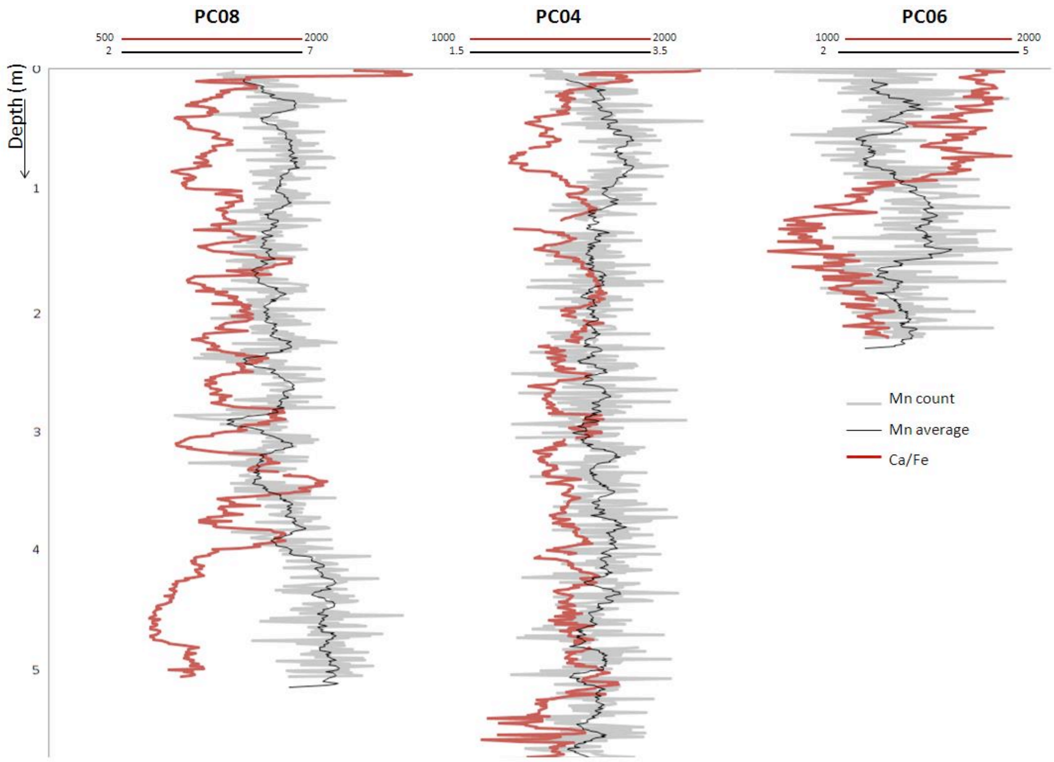


Figure 5.11: Mn curves plotted with Ca/Fe for the three piston cores. High Mn values may indicate times when the region was swept by well-oxygenated bottom waters. (Janson et al. 1998; Richter et al. 2006).

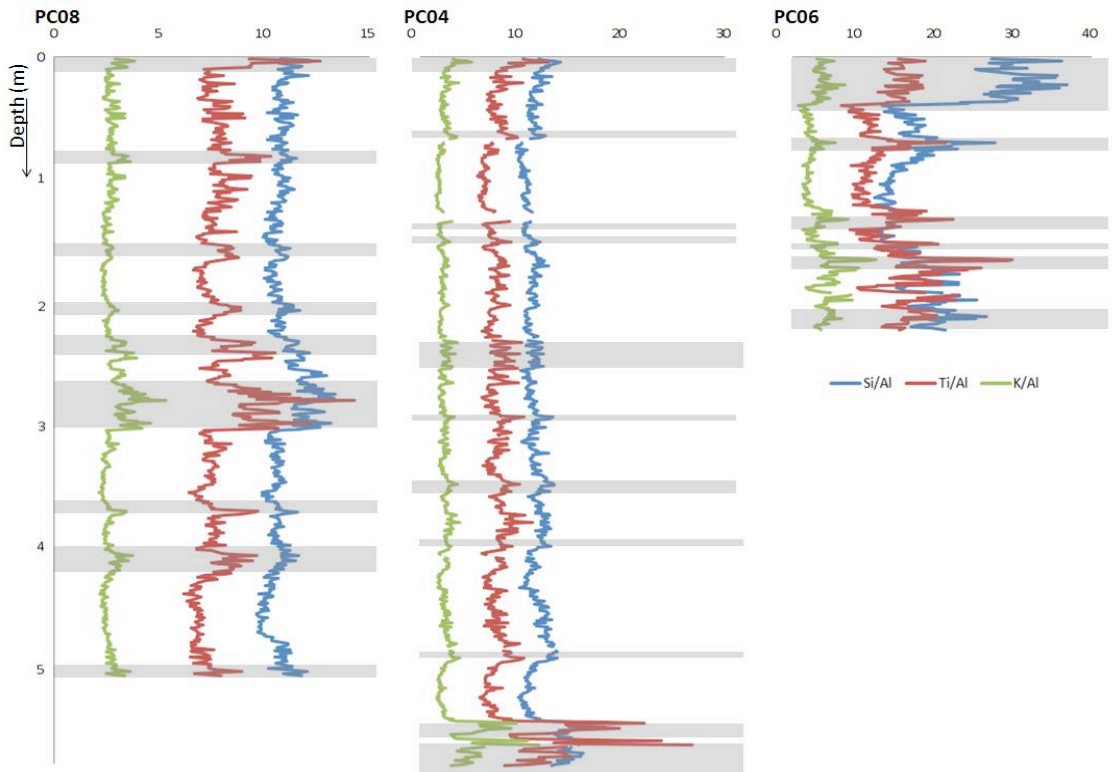


Figure 5.12: Coincident Si/Al (blue), Ti/Al (red) and K/Al (green) peaks may relate to times of enhanced winnowing (shaded in grey) (Wehausen and Brumsack 1999).

5.2.1.2 Cross Plotting

The elemental composition of the sediment can give clues to changing provenance. For example, Wehausen and Brumsack (1999) observed high Si/Al and Zr/Al ratios during times of Sahara dust influx, versus high Mg/Al ratios at times of enhanced fluvial run-off in their study in the eastern Mediterranean. This has been linked to climatic fluctuations between times of dry and more humid conditions. They can also distinguish between sediments sourced from the northern and southern margins of the Mediterranean Sea.

Here, we use cross plots to accentuate any differences in chemical composition between cores and sedimentary units. The most successful cross plots constructed in this study is that of Si/Al against Ca/K that can be used to approximate sediment composition (Fig. 5.13). The plot shows the results for PC04, PC06 and PC08 and considerable differences in composition can be observed. PC04 and PC08 are both located in the midslope and plot in a similar clustering. This is in contrast with the data from upper slope site PC06 which shows two distinct trends.

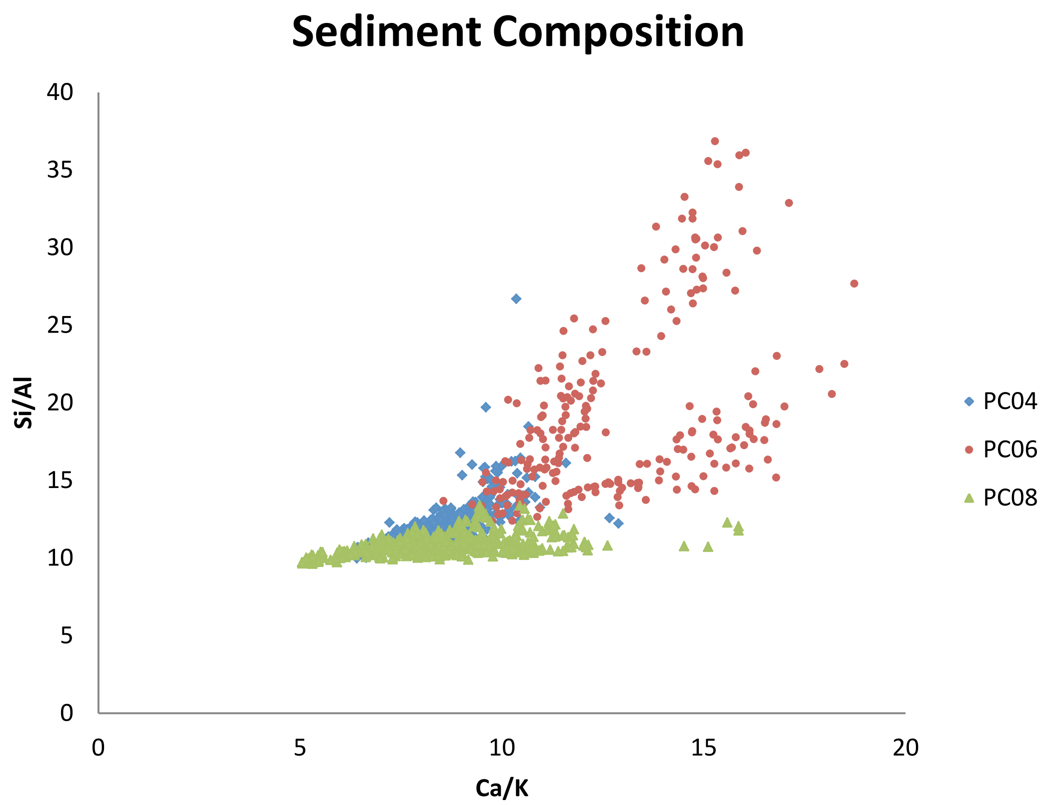


Figure 5.13: Cross plot of Si/Al against Ca/K. The three piston cores PC04, PC06 and PC08 are plotted. Results indicate that PC06 is of a different composition.

5.2.2 Smear-Slide Results

A complete sedimentological analysis was carried out for 25 samples under the petrological microscope with data and photographs assembled in Appendix 5. They are summarised in Figure 5.14. Main results for each unit in the gravity cores are outlined below.

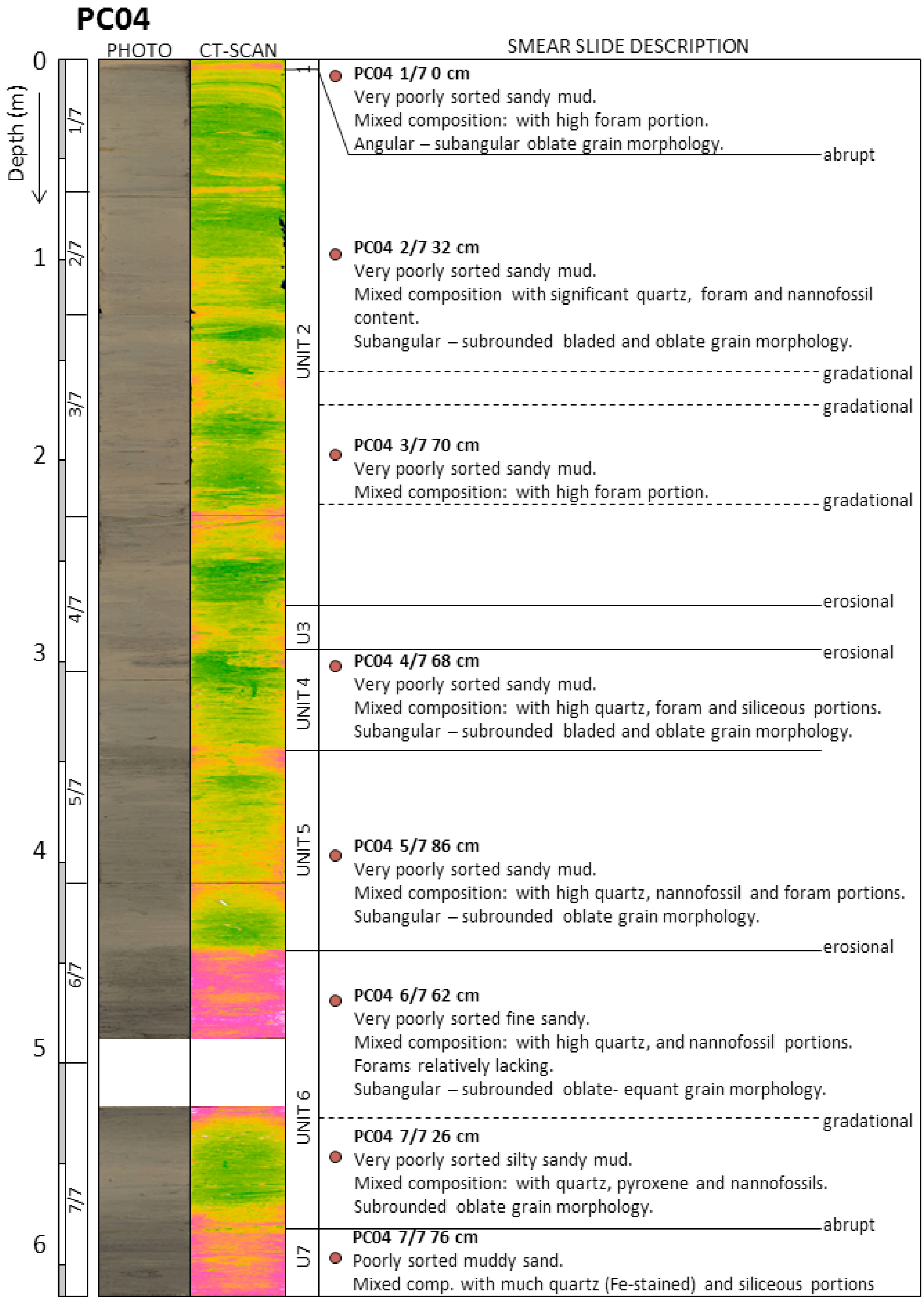
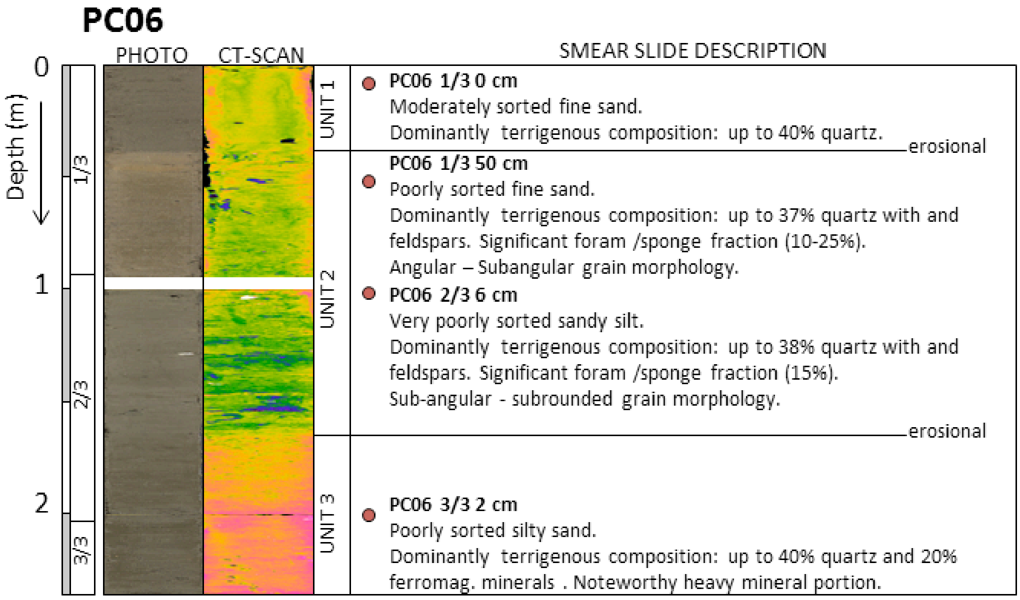
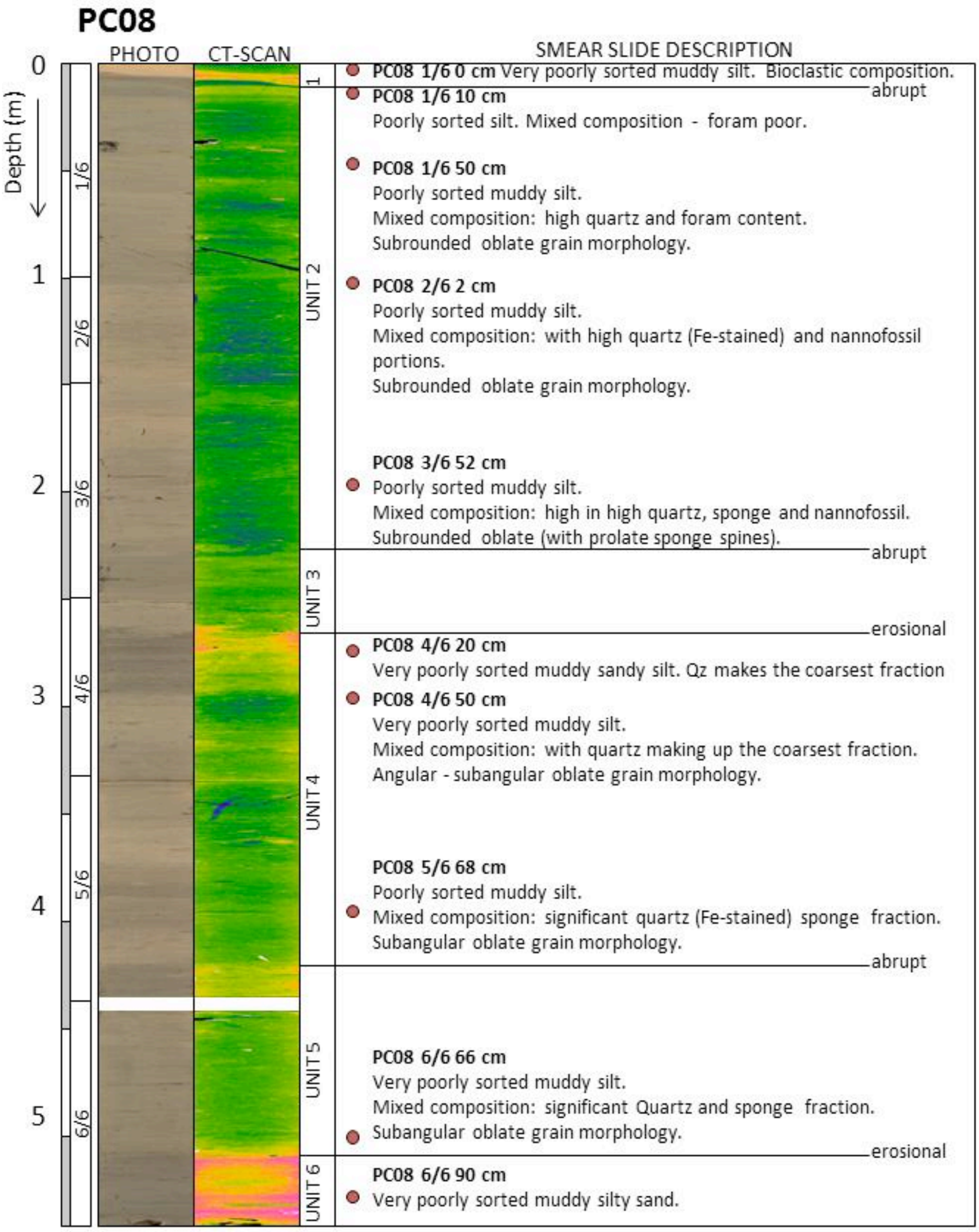


Figure 5.14: (continued overleaf) Summary of the smear slide analysis carried out on the piston cores. Analysis has been used to aid the identification of distinct units in each of the cores


PC06
PHOTO
CT-SCAN
SMEAR SLIDE DESCRIPTION
Depth (m)
0
1
2
1/3
2/3
3/3
UNIT 1
UNIT 2
UNIT 3
PC06 1/3 0 cm
Moderately sorted fine sand.
Dominantly terrigenous composition: up to 40% quartz.
erosional
PC06 1/3 50 cm
Poorly sorted fine sand.
Dominantly terrigenous composition: up to 37% quartz with and feldspars. Significant foram /sponge fraction (10-25%).
Angular – Subangular grain morphology.
PC06 2/3 6 cm
Very poorly sorted sandy silt.
Dominantly terrigenous composition: up to 38% quartz with and feldspars. Significant foram /sponge fraction (15%).
Sub-angular - subrounded grain morphology.
erosional
PC06 3/3 2 cm
Poorly sorted silty sand.
Dominantly terrigenous composition: up to 40% quartz and 20% ferromag. minerals . Noteworthy heavy mineral portion.


PC08
PHOTO
CT-SCAN
SMEAR SLIDE DESCRIPTION
Depth (m)
0
1
2
3
4
5
1/6
2/6
3/6
4/6
5/6
6/6
1
UNIT 2
UNIT 3
UNIT 4
UNIT 5
UNIT 6
PC08 1/6 0 cm Very poorly sorted muddy silt. Bioclastic composition.
abrupt
PC08 1/6 10 cm
Poorly sorted silt. Mixed composition - foram poor.
PC08 1/6 50 cm
Poorly sorted muddy silt.
Mixed composition: high quartz and foram content.
Subrounded oblate grain morphology.
PC08 2/6 2 cm
Poorly sorted muddy silt.
Mixed composition: with high quartz (Fe-stained) and nannofossil portions.
Subrounded oblate grain morphology.
PC08 3/6 52 cm
Poorly sorted muddy silt.
Mixed composition: high in high quartz, sponge and nannofossil.
Subrounded oblate (with prolate sponge spines).
abrupt
erosional
PC08 4/6 20 cm
Very poorly sorted muddy sandy silt. Qz makes the coarsest fraction
PC08 4/6 50 cm
Very poorly sorted muddy silt.
Mixed composition: with quartz making up the coarsest fraction.
Angular - subangular oblate grain morphology.
PC08 5/6 68 cm
Poorly sorted muddy silt.
Mixed composition: significant quartz (Fe-stained) sponge fraction.
Subangular oblate grain morphology.
abrupt
PC08 6/6 66 cm
Very poorly sorted muddy silt.
Mixed composition: significant Quartz and sponge fraction.
Subangular oblate grain morphology.
erosional
PC08 6/6 90 cm
Very poorly sorted muddy silty sand.

5.2.2.1 PC06

The upper slope piston core PC06 is made up of three units that are separated by erosional surfaces (Fig. 5.14). Unit 1 is 40 cm thick and consists of moderately sorted fine sand. Compositionally, this unit is dominated by terrigenous sediment (quartz, feldspars). There is a minor shelly fragment and a foraminifera component also. This unit differs greatly from the underlying unit 2 – a very poorly-sorted muddy sand. Unit 2 maintains a mixed composition, but has a much larger bioclastic component, mainly siliceous sponge fragments and foraminifera. An underlying silty sand below (unit 3) shows poor sorting and another increase in the terrigenous portion.

5.2.2.2 PC04

Piston core PC04 shows seven units separated by both erosional and gradational boundaries. Eight samples were examined in detail to characterise these units (Fig. 5.14). A thin 30 cm tan-brown unit tops the succession (unit 1). On analysis of the associated trigger core, this unit reaches *35 cm* in thickness (Fig. 5.14 F; 5.15). Unit 2 is the thickest at 2.53 m thick. It is predominately composed of very poorly sorted sandy mud. Within this unit there a gradational changes towards sandy silts. The sediment is of mixed composition with a significant foraminifera portion, in addition to quartz and other terrigenous clasts. The underlying units 3, 4 and 5 are much thinner: 0.25, 0.48 and 1.1 m respectively. Each is separated by an erosional surface and appears to be of similar composition to the overlying unit 2 with fine sandy muds dominating with sections of higher portions of sand. Unit 6 is separated from the overlying unit by an abrupt erosional surface and consists of silty mud grading upwards to a very poorly sorted silty fine sand. The lowermost unit 7 is a muddy sand and has a similar composition to the overlying units with significant quartz and nannofossil portions. In the sandy sections, foraminifers are relatively lacking, and in the lower sandy section, quartz grains are iron-stained.

5.2.2.3 PC08

Ten samples were examined from PC08. Despite being the finest-grained of the sediment cores, PC08 is still shows six distinct units separated by erosional and abrupt boundaries (Fig. 5.14). Unit 1 is only 6 cm thick in PC09 but reaching 43 cm in the trigger core (Fig. 5.4 G; 5.5). It is composed of very poorly muddy silt with a dominantly bioclastic composition (nannofossils, forams, silicious sponge fragments and bryzoa). It has a distinct tan colour in core as with unit 1 in PC04. This is separated from the underlying unit 2 by an abrupt (but with no evidence for being erosive) boundary. Unit 2 is approximately 1.25 m thick and is a poorly sorted muddy silt with localised cleaner silts. It is of mixed silici-bioclastic composition with notable quartz, foraminifera and nannofossil (coccolith) portions. Units 3 and 4 show a move to coarser sediment accumulation with very poorly to poorly sorted muddy silts. The boundary between unit 3 and 4 appears erosional with unit 4 being topped by a muddy sand, and grading down the core back to muddy silt. Quartz tends to make up the coarsest position of the sediment and can be iron-stained. The base of unit 4 at 5.1 m shows another abrupt grain size change and the underlying unit 5 is a coarsening upwards succession from muddy silt to muddy fine sand. The lowermost unit 6 is also the coarsest in PC08. It is a very poorly sorted muddy fine sand of mixed composition separated from the overlying unit 5 by an erosional boundary (Fig. 5.14).

5.2.2.4 BC05

The coarsest of the sediment samples to be analysed under the microscope were from BC05. The box core was sampled upon acquisition, and therefore no core logging carried out. However, the grain size analysis indicates that it consists of one unit. It is composed of medium to coarse sands, with a section of coarser average grain size between 10 and 18 cm core depth. The composition looks to be largely quartz with bioclastic material. The largest grain sizes (coarse to very coarse sand portion) are predominantly shelly debris.

5.3 Sediment Texture

5.3.1 Grain Size Distribution Parameters

The mean grain size for each core is plotted against depth in Fig. 5.15. The results were mainly used to identify facies, aid logging and construct cross plots (see below). Key results show that the mid slope BC05 and upper slope PC06 shows the highest average grain sizes. PC08, located at the deepest core site, has the lowest average grain sizes.

The Gulf of Cadiz samples show standard deviation ranges from 1.8 to 5.4; moderately sorted to very poorly sorted. When plotted with mean grain size the sorting results show that the cores have very different responses to this relationship (Fig. 5.15) and these are clearly images when they are cross plot against each other (Fig. 5.16 A). PC08, the deepest and most mud-rich of the piston cores shows that with increasing average grain size, there is a *decrease* in sediment sorting. The same is true for the upper 4.5 m of PC04. PC06 and the lowermost metre of PC04, clearly show a strong pairing where higher average grain size corresponds to better sorting (Fig. 5.15).

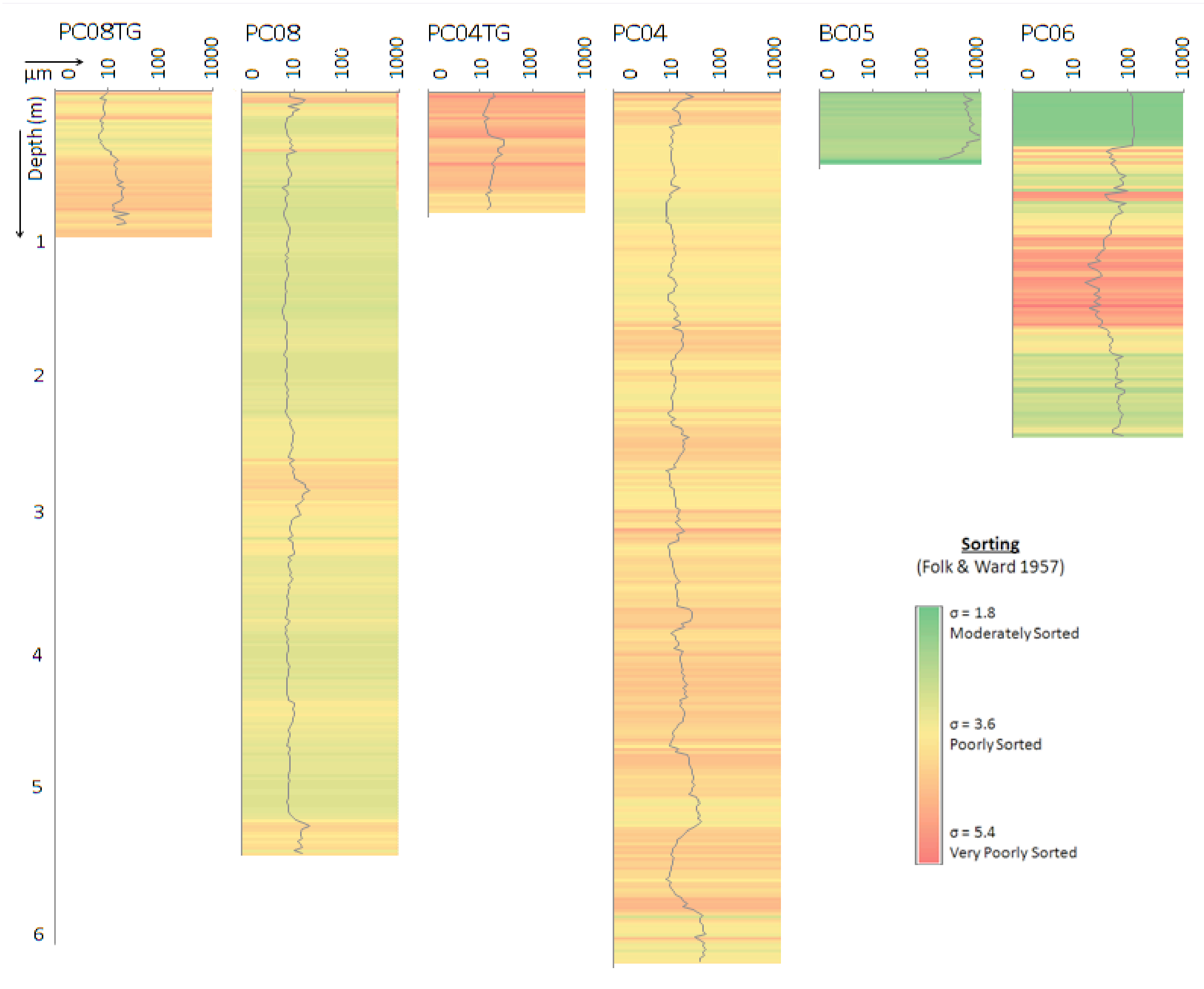


Figure 5.15: Sorting plot using a colour scale with an average grain size curve. Measurements were made on a 2cm resolution. Some sections show increasing sorting with increasing grain size, whereas others show decreasing sorting with increasing grain size.

The topmost bed of PC06 (a fine sand) shows the best degree of sorting – reaching a σ low of 1.824, or moderately sorted. BC05 also shows better sorting than the other cores. The remainder of PC06 rarely shows mean grain sizes smaller than coarse silt (<31µm) or medium silt (<15.6 µm). The same can be said for the lowermost metre of PC04. Therefore, the fine silt (<15.6 µm) and muddy (<3.9 µm) sections show a very different pattern of sorting to the coarser sections in PC06 and the lowermost metre of PC04. Medium- and coarse-silt diameters largely correlate to McCave's 'sortable silt' fraction for which a flow velocity control has been proposed (McCave 2008). We can deduce from PC06 that, in general, with increasing sand comes a significant increase in sediment sorting. The relationship is complicated however by two separate trends being seen in the PC06 mean grain size vs sorting cross plots (Fig. 5.16 A). Both these trends are distinct from the PC04 and PC08 trend. The distribution curves (plotted on a geometric scale) are shown in Fig. 5.17 for each core at 50 cm intervals (or 10 cm in the case of BC05). They illustrate the increased sorting in the sand-rich beds.

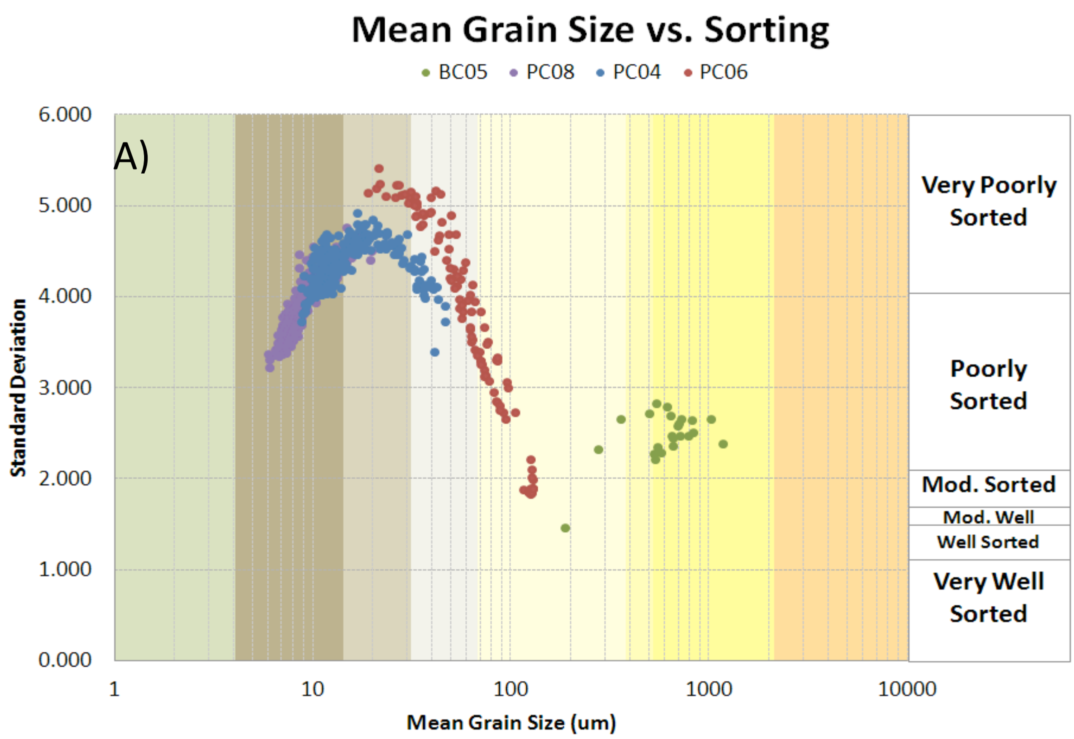


Figure 5.16 (continued overleaf)

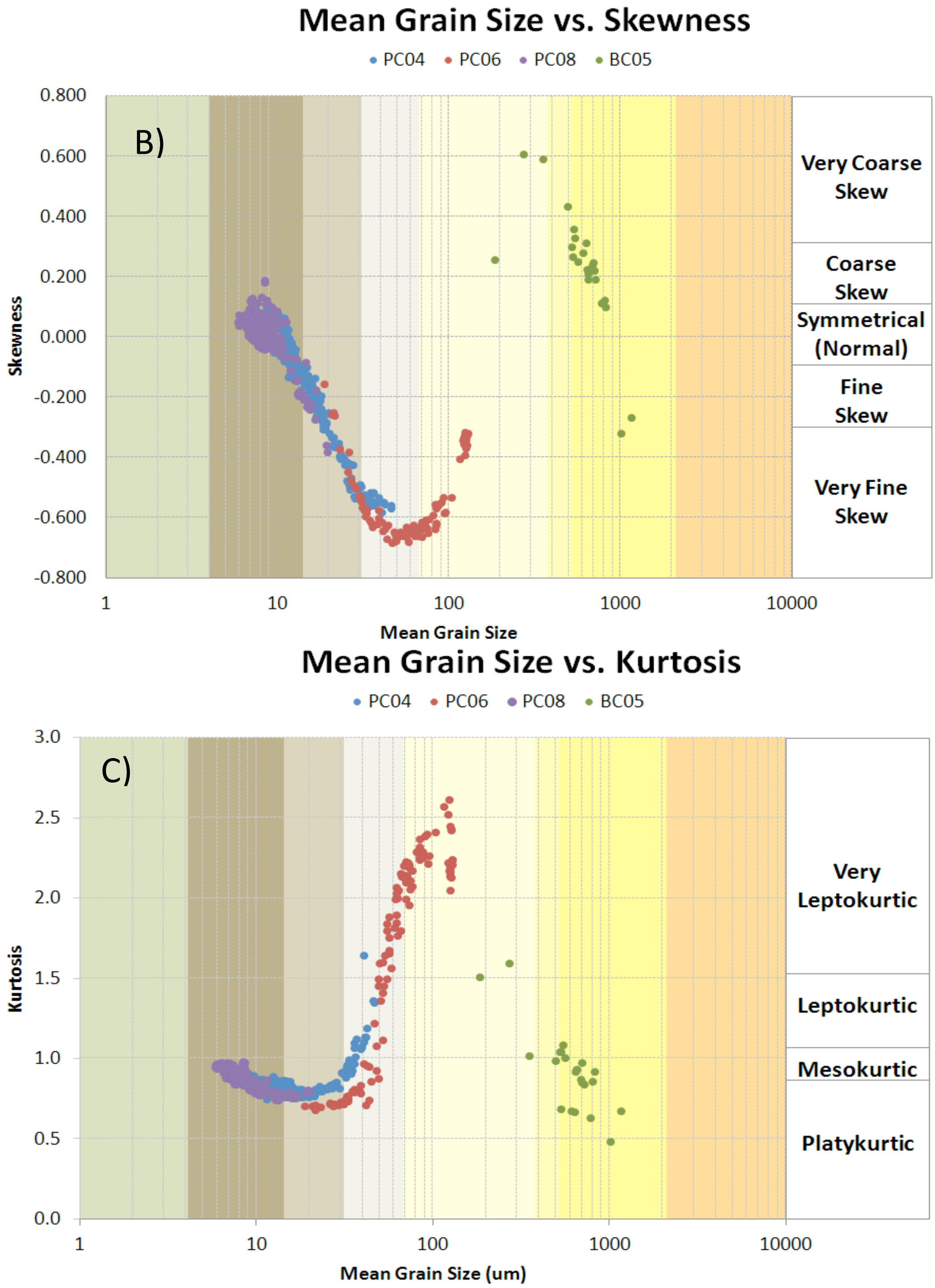


Figure 5.16: A). Cross plot of the sorting against mean grain size reveals that mud and fine silt has a negative relationship with sorting and medium silt to fine sand has a positive association with sorting. B) Mean grain size vs. skewness. Finest grain sizes show a minor coarse tail or near-normal distribution. The majority of the samples show a fine skew. C) Mean grain size vs. kurtosis. Coarse grain sizes show a higher concentration of grain sizes around the mean whereas the finer sediments show a broader (platykurtic) spread.

Skewness data appears to have a complex relationship with both mean grain size (Fig. 5.16 B) and the first mode (Fig. 5.17). Skewness has also been cross plotted against sorting, this time plotted for grain size rather than core site so that the control of grain size can be imaged clearly (Fig. 5.19). Medium to coarse sands plot quite separately from the bulk of the data. Fine sands show the best degree of sorting, but very fine sands are highly variable and range from very poorly to moderately sorted. These very fine sands have the finest skew values, whereas fine silts have the coarsest skew. Skewness appears to be returning to normal distribution with grain size within the silt fraction. There appears to be a number of different trends. Specifically, silts react very differently from sands and sorting decreases with increasing grain size. The sand portion appears to show thee distinct trends.

The kurtosis values measured from the sediment distributions range from 0.675 (platykurtic) to 2.609 (vey leptokurtic). Figure 5.16 C shows the relationship between mean grain size and kurtosis. Fine sands show the highest concentration of data around the mean whereas the finer and coarser sediments show a broader (platykurtic) spread. Kurtosis has been plotted against skewness and shows interesting relationships, this time plotted for grain size rather than core site (Fig. 5.20). A number of distinct trends are seen in the data. Specifically, a concentration of fine sand data points is seen to plot quite separately from the rest the data. The majority of the data plots along two trend lines (Fig. 5.20).

5.3.2 Clay Fraction

It should be noted that, as is common with laser particle size analysis, the clay fraction is not wholly represented. Measurements in this study begin at 0.05 µm. However, the grain size distribution curves show a tailing off towards the finer sediment and therefore it is unlikely that there is a significant component finer that 0.05 µm and that the fine-scale fraction recorded is a good representation of the true content of this sand-rich contourite depositional system. This is backed-up by smear slide observations.

5.3.3 Cumulative Frequency Curves

Figure 5.21 shows cumulative frequency curves for all the samples (from the three piston cores and one box core) as divided by their *average* grain size. The graphs show considerable changes in the curve depending on the average grain size. Finer sediments show characteristically smooth curves. With coarsening sediment, changes in the trend of the cumulative distribution are seen (Fig. 5.21) and will be discussed further in Chapter 9.

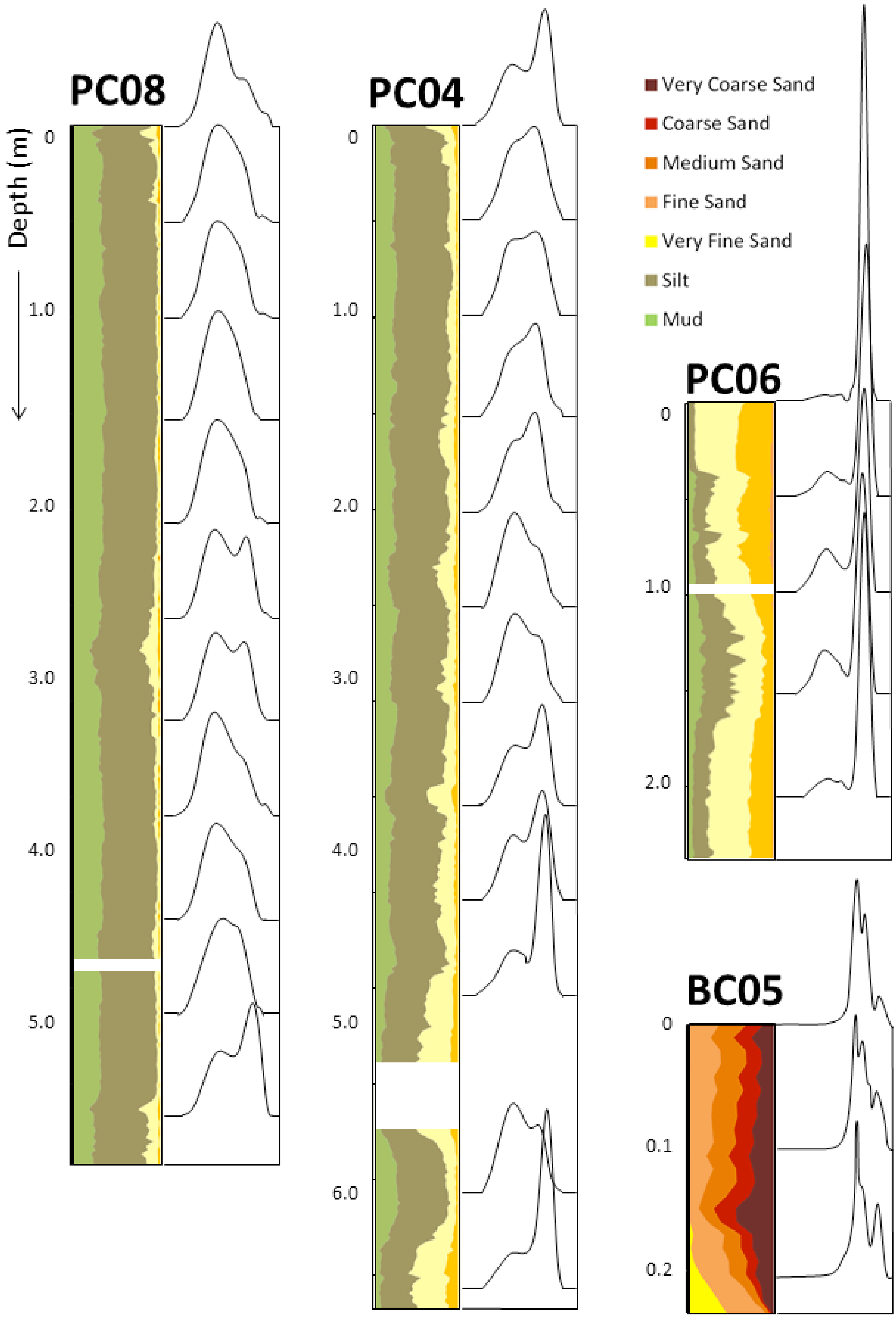


Figure 5.17: The grain size break-down and distribution curves (plotted on a geometric scale) for each core at 50 cm intervals (or 10 cm in the case of BC05). Note the changing vertical scales.

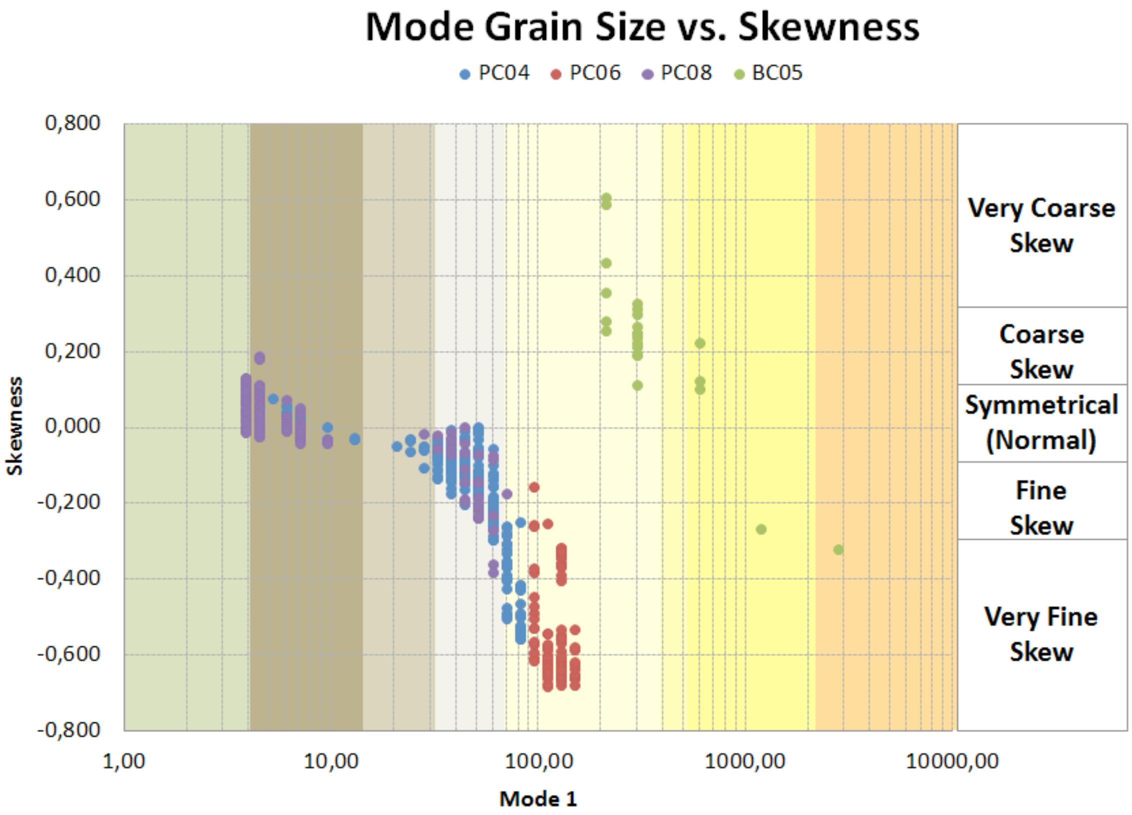


Figure 5.18: Mode grain size (mode 1 where there are multiple modes) plotted against skewness. There is an increase in fine skew with mode until approx. 110 µm.

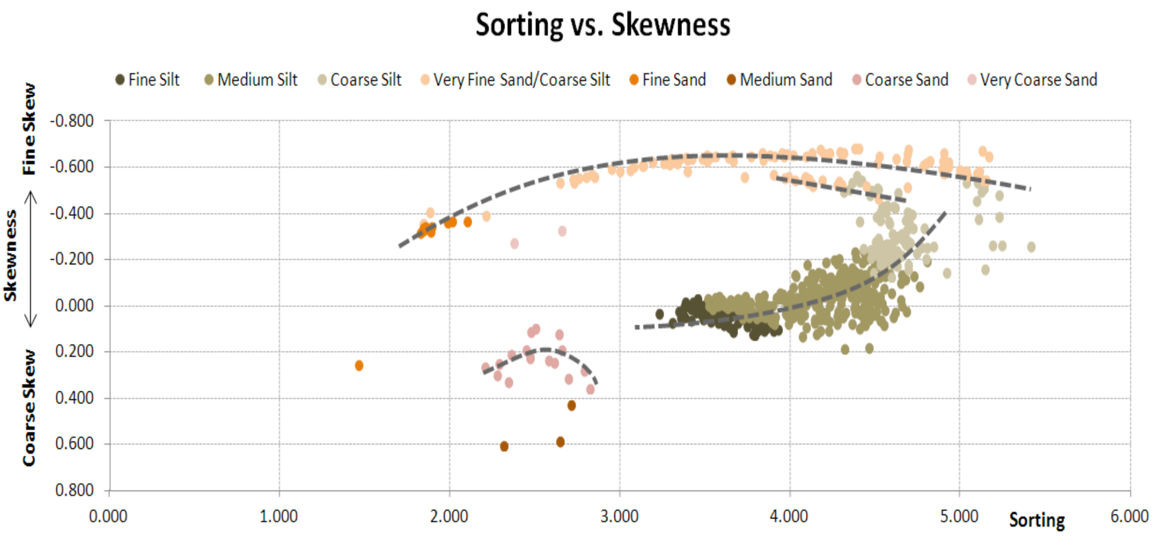


Figure 5.19: Sorting vs. skewness cross plot showing multiple trends. Data points are colour-coded with respect to mean grain size, and there appears to be a direct link between cross plot trends and mean grain size.

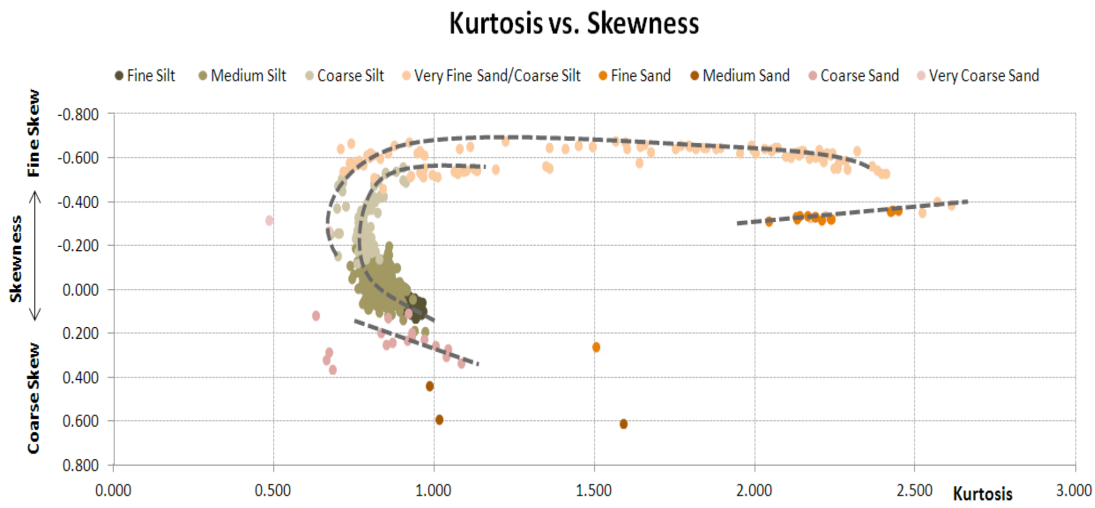


Figure 5.20: Kurtosis vs. skewness cross plot showing multiple trends. Data points are colour-coded with respect to mean grain size.

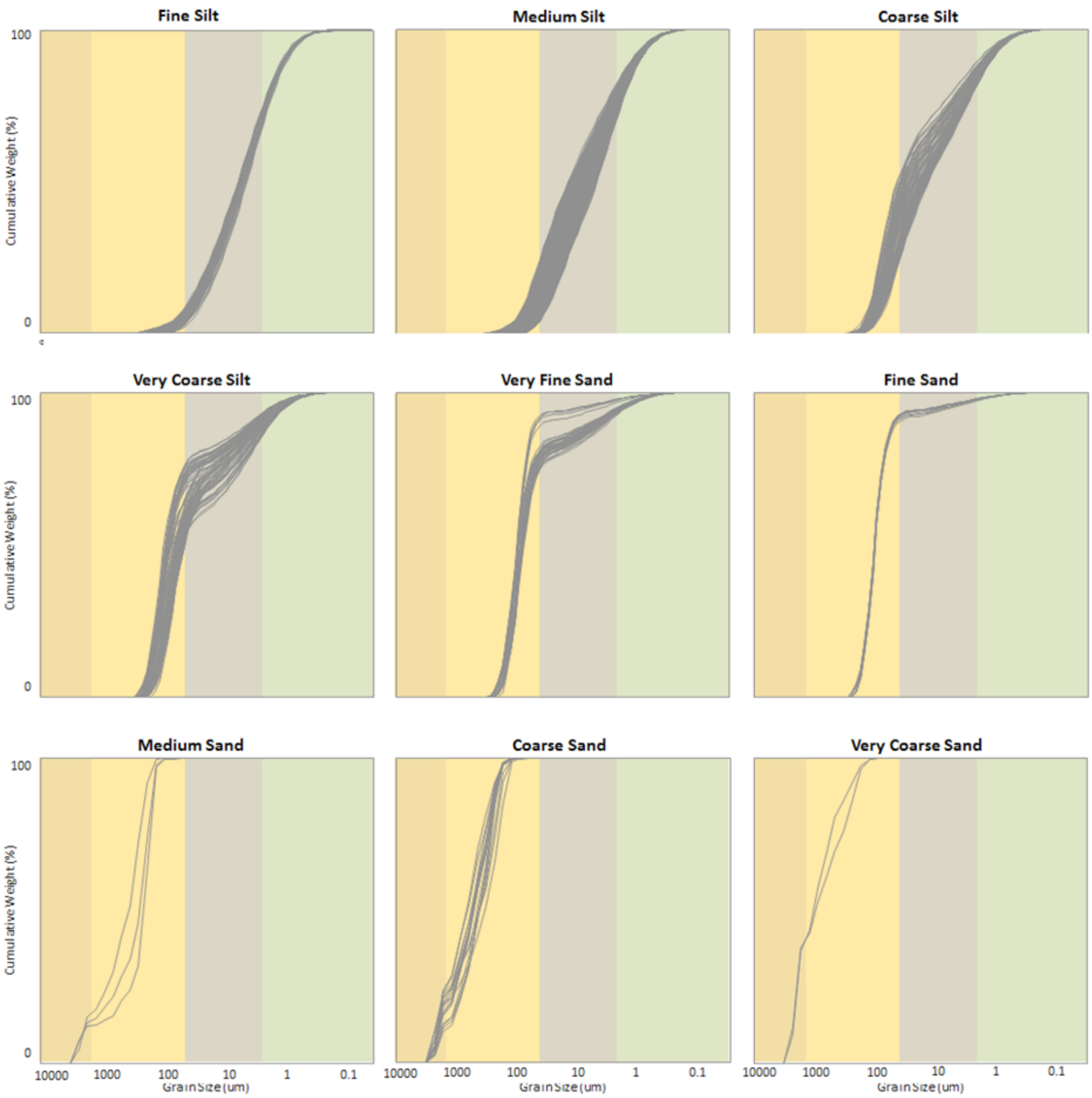


Figure 5.21: Cumulative frequency curves for each average grain size division across all gravity core sites.

The main results for the grain size analysis are therefore;

1. Average grain sizes across the eastern Gulf of Cadiz range from fine silt to very coarse sand.
2. Sorting ranges from very poorly to moderately sorted. Fine sands show the highest degree of sorting.
3. There is a complex association between mean grain size and the other parameters that may be due to depositional processes.
4. Muds show symmetrical grain size distributions, whereas silts and fine sands are finely skewed. Medium to coarse sands show a coarse skew.
5. Cumulative frequency curves show changing trends depending on the mean grain size.

5.4 Dating

5.4.1 Core Dating

In total, fifteen samples were submitted for radiocarbon dating. Three each from PC06 and U1388, five from PC04, and four from PC08 (Table 5.3). Coarse-grained BC05 was thought to consist of large amounts of reworked material, and was therefore unsuitable to allow for accurate dating and was excluded from the analysis. The fifteen samples that were collected show error bars up to 1400 yrs. BP which are negligible (Table 5.3). The results show that the piston cores are Quaternary and reach a maximum recorded age of 45,900 ±1400 BP, which is dated at Latest Pleistocene (Tarantian). The triggers to the piston cores were not dated, and therefore an assumption has been made that the additional trigger core thickness is younging towards present day.

There are a number of anomalous points (Fig. 5.22), and an additional run of dating was required to give a better accuracy of the dates. These anomalous points are likely due to an unexpectedly high level of sediment re-working within the system. Nevertheless, a low resolution understanding of the age of the sediments has been reached with best-fit lines (Fig. 5.22).

The dates can be used to aid correlation between cores. Each core has a number of erosional surfaces and distinctive sand and/or mud-dominated beds. Dating gives a first idea of the correlation between the piston cores and an indication on whether individual beds can be correlated between cores (see Chapter 6). The dates can also give some insight into the sediment accumulation rates, as outlined below.

Core	Sample	14 C age (BP)	Error ±
PC06	1/3 36-38 cm	5525	28
	2/3 58-60 cm	9585	29
	3/3 32-34 cm	10645	35
U1388	A1H1 8-10 cm	8390	40
	A1H3 25-27 cm	7990	45
	B3X1 5-7 cm	42220	950
PC04	1/7 4-6 cm	11292	30
	5/7 50-52 cm	34279	183
	6/7 34-36cm	35212	196
	7/7 84-86 cm	35750	470
	7/7 88-90 cm	31740	140
PC08	1/6 4-6 cm	4973	28
	4/6 16-18 cm	39032	305
	6/6 86-88 cm	45900	1400
	6/6 94-96 cm	22652	57

Table 5.3: ^{14}C dates and errors acquired from four cores across the eastern Gulf of Cadiz. Dates in grey are from the SUERC Radiocarbon Facility and those in blue from the Laboratoire de Mesure du Carbone 14.

5.4.2 Rates of deposition

The dates show that depositional rates are very different between the core sites. The two upper slope cores, PC06 and U1388 show high sedimentation rates throughout the Holocene (Fig. 5.23). Core PC06, located on an upper slope plastered drift, has an accumulation rate of 36.72 cm/ka and is completely Holocene in age. An inconsistency in the dating of U1388, which is located in the northern contourite channel, has led to no accurate accumulation rates being calculated. However, It appears that there is a much higher rate of deposition in the Holocene (estimated ~100 cm/ka) when compared to the Pleistocene (estimates ~10 cm/ka) core has the highest depositional rate and a huge amount of sediment reworking. Inconsistencies in the data for this core are thought to be due to sediment re-working and very rapid deposition rates.

Cores PC04 and PC08 are both located on a midslope mounded drift. They show very different accumulation trends compared to the upper slope cores (Fig. 5.23). Holocene and Upper Pleistocene (approximately until 30,000- 40,000 yrs BP) have relatively low rates of deposition: 13.49 cm/ka in PC04 and 7.54 cm/ka in PC08. Both show an increase in accumulation rates in the lower portion of the core: 141.4 cm/ka and 35.5 cm/ka for PC04 and PC08 respectively. PC08, the deepest of all the dated cores, shows the slowest overall accumulation rates.

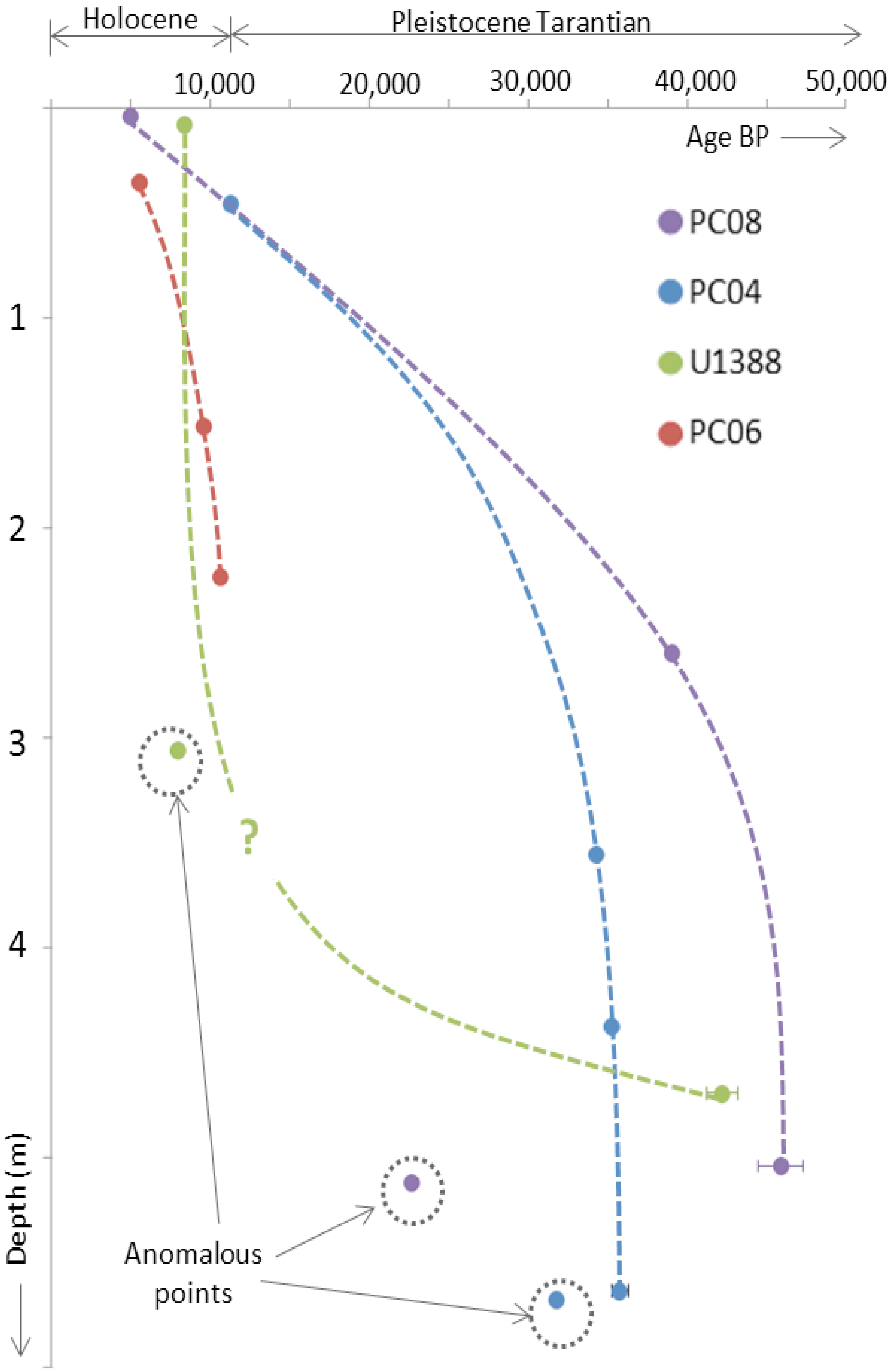


Figure 5.22: Sediment sample ages as measured by ^{14}C plotted against depth for each core.

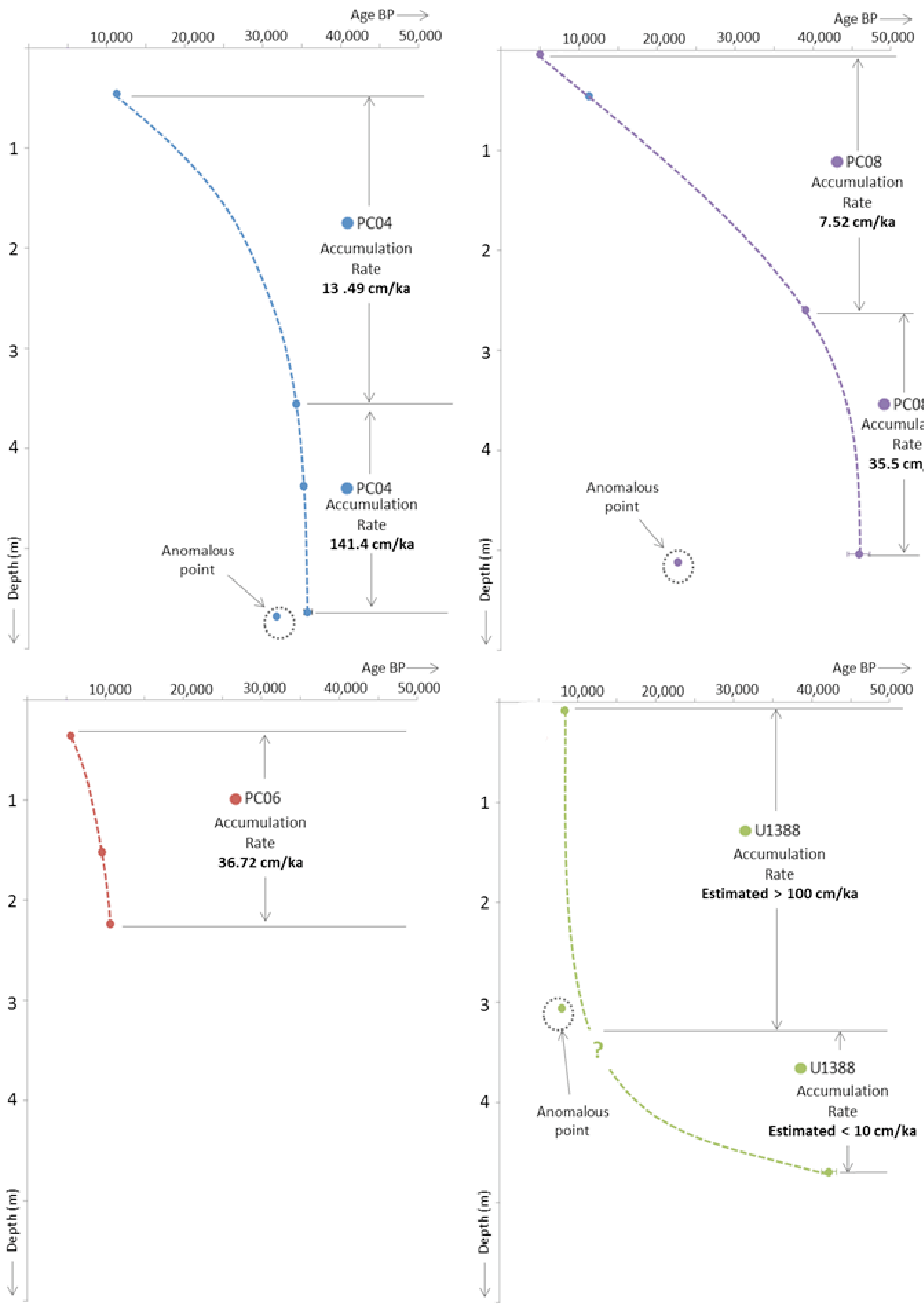


Figure 5.23: Accumulation rates for the dated sediment cores.

Interpretation & Discussion

6 The Gulf of Cadiz Sandy Contourite Depositional System.

6.1 Introduction

Using the sedimentological and acoustic results that are outlined in chapters 4-5, a better understanding of the Gulf of Cadiz contourite depositional system can be gained. This chapter will examine and discuss two separate regions: 1) The present day and Quaternary evolution of the eastern Gulf of Cadiz sandy contourite depositional system; and 2) The large-scale evolution of a buried Pliocene system along the Algarve Margin in the north. The wider implications of the findings will be discussed with relation to the evolution of the Gulf of Cadiz contourite depositional system and the controls on sand distribution.

Although research has been ongoing in the Gulf of Cadiz for many decades, there has yet to be a thorough study on the most eastern portion of the region that incorporates the entire continental slope, and the current scientific understanding of the upper and midslope features remains poorly known. Figure 6.1 highlights key detailed studies across the wider Gulf of Cadiz area. Work has been carried out on the continental shelf adjacent to our area of interest (Nelson et al. 1999; Lobo et al. 2010; Lobo and Ridente 2014), and at depth across the lower slope (Habgood et al. 2003; Rogerson et al. 2011). This study will provide a missing link between the shelf and lower slope and a better understanding of the interactions between along and downslope processes in the eastern Gulf of Cadiz. It will also link the Strait of Gibraltar to studies carried out in the central and western Gulf of Cadiz (Nelson et al. 1993; Llave et al. 2007c; Stow et al. 2013b) (Fig. 6.1).

The midslope of the Algarve margin, in the north of the Gulf of Cadiz, is today dominated by the mud-rich Faro-Albufeira elongate mounded drift and associated erosional contourite moat (the Alvarez-Cabral moat) (Fig. 4.5). It is indicative of a much lower-energy system when compared to the eastern Gulf of Cadiz which is influenced by a vigorous MOW after the exit of the Gibraltar Gateway. The elongate mounded drifts have been characterised in detail over the years and have been dated as Quaternary in age. The underlying Pliocene section however, has been largely overlooked. This section documents the initiation of the influence of the MOW over the margin after the opening of the Gibraltar Gateway in the latest Miocene. Results from the seismic grid used in this study (Section 4.2) show a number of seismic units and acoustic

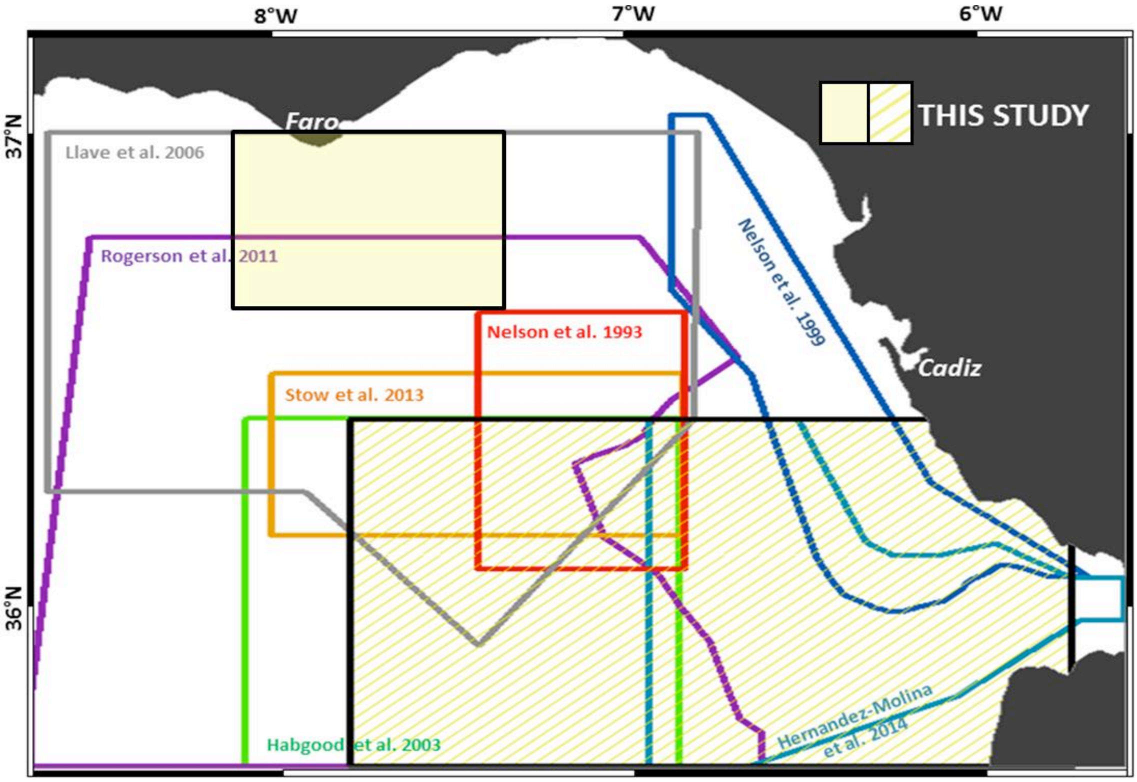


Figure 6.1: The area of interest for this study is shaded and will act to join the prior studies of the shelf and lower slope. (Nelson et al. 1993; Stow et al. 2002b; 2013b ; Habgood et al. 2003; Rogerson et al. 2011; Hernández-Molina et al. 2014).

facies. Their interpretation and implications are discussed here. This work has largely been published in the Brackenridge et al. (2013b) Marine and Petroleum Geology paper '*A Pliocene mixed contourite-turbidite system offshore the Algarve Margin, Gulf of Cadiz: Seismic response, margin evolution and reservoir implications*'.

Although these two studies have been carried out on different scales, care will be taken to note any contrasts (and similarities) of the two systems. The interpretation will also be used to evaluate the characterisation, controls, and importance of contourite sand deposition in chapters 7-9.

6.2 Interpretation

6.2.1 Acoustic Data Analysis

6.2.1.1 Eastern Gulf of Cadiz

6.2.1.1.1 Morphological features

A number of large-scale features are identified on the bathymetric data-set that have been interpreted by Hernández-Molina et al. (2014) (Fig. 2.7). Two terraces (an upper and a lower) dominate the midslope. Below this erosive surface, a thick (>800 m) contourite sand sheet is found (Antich et al. 2005; Stow et al. 2011). Basement outcrop and coarser-grained sediment (sands and gravels) are identified on account of their higher backscatter compared to finer sediment (Medialdea et al. 2008). As a result, coarser areas are associated with acoustic data that shows higher amplitude sea bed reflectors and lower penetration (Table 6.1).

The upper terrace deepens northwestward (from 500 - 730 m) and varies between 13.5 and 23 km in width. It slopes seaward at a gradient of 0.18-0.34°. The lower terrace also deepens northwestward, from 585 m to 750 m. This terrace is ~9 km wide and slopes seawards between 0.18° and 0.45°. Each terrace shows a similar set of repeating features with depth: a basinward-dipping erosional surface, an alongslope orientated channel, and a smooth mounded drift adjacent to the channel. They also show multiple small furrows oblique to the channel orientation at 30°–45° (Fig. 2.7). The *lower terrace* has larger and better defined features than the *upper terrace*. The large and incised southern *main channel* is ~6 km wide (Fig. 4.3 B) and is characterised by its broadly sinusoidal shape and westsouthwest to northwest trend. Its axis slopes from 715 m to 780 m and eventually feeds into the Cadiz contourite channel in the central 'channels and ridges sector' (Fig. 2.6). Seaward of the main channel, an associated mounded drift is characterised by irregular morphology and sediment waves (Fig. 4.3 B). The drift crest deepens westward from 600 m to 830 m. The *northern channel* is less distinct and shorter, becoming more established toward the northwest, where it feeds into the Cadiz and Guadalquivir contourite channels (Fig. 2.6). Its axis deepens from 500 m to 780 m, and it is also bounded on its seaward flank by a mounded drift (albeit much smaller than the lower drift) (Fig. 4.3 A). The crest of this drift also deepens northwestwards from 530 to 650 m (Hernández-Molina et al. 2014).

6.2.1.1.2 Seismic facies

The parasound data shows a cross section through the lower slope in a NW-SE (Fig. 4.2 A) and a NE-SW orientation (Fig. 4.2 B). The internal and external morphology of the lowermost slope is dominated by migrating sediment waves towards the NW. These show subtle downlapping surfaces, high frequency parallel bedding in the subsurface, and a wavy external morphology (Table 6.1). Across this depositional-dominated region there are occasional incising channels with a downslope or oblique orientation (Fig. 4.2 A). By far the most striking morphological feature of these lines is the large alongslope-orientated channel (Fig. 4.2 B) that cuts into the sediment with a steep south-westerly side and a shallower-gradient or stepped north-eastern bank. It is characterised by a highly uneven sea bed reflector showing hyperbolic response, variable amplitudes and low penetration, with a generally low quality acoustic response (Table 6.1). Moving upslope of this contourite channel is an area of low sea floor gradient and

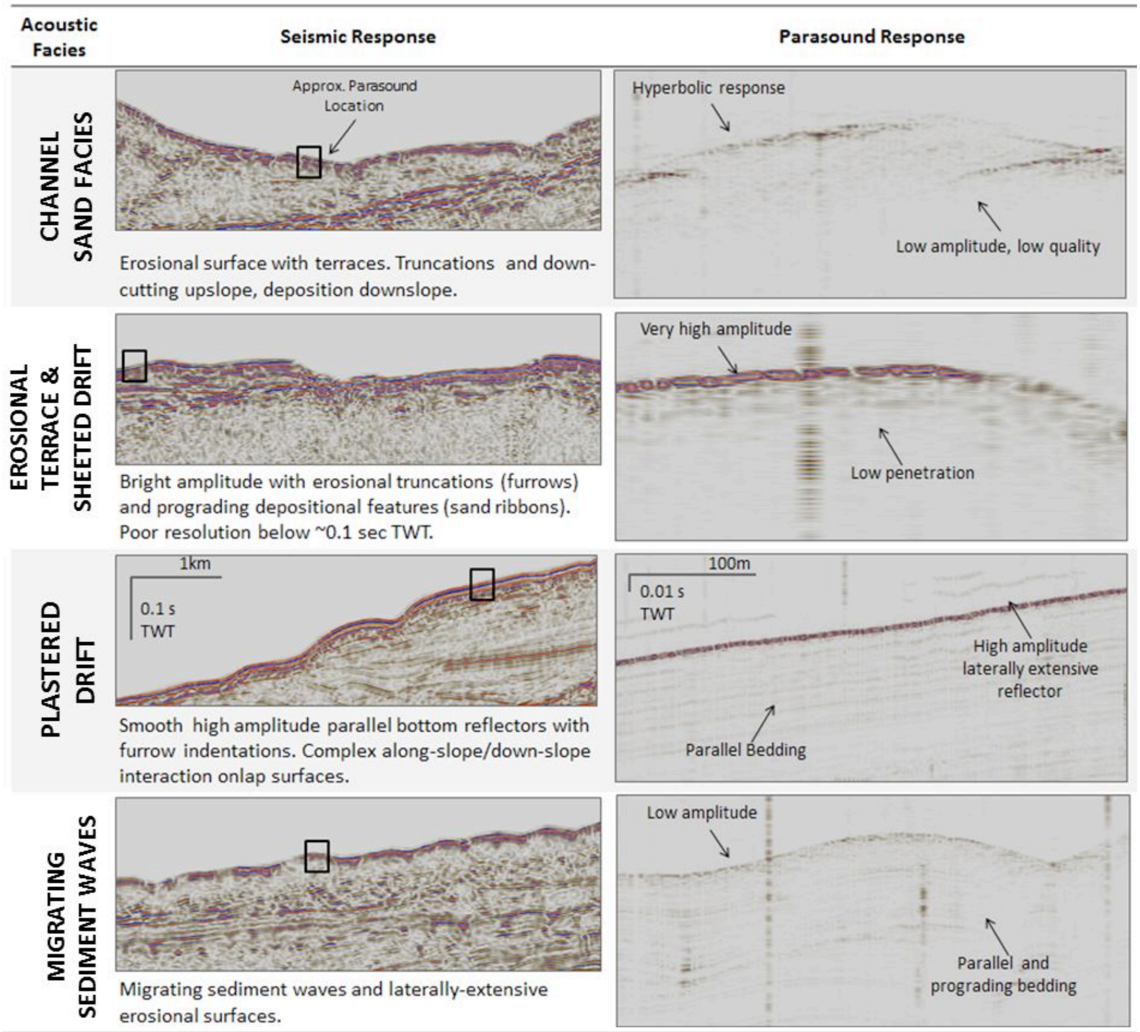


Table 6.1: Seismic and acoustic facies across the eastern Gulf of Cadiz.

complex morphology. This uneven terraced surface is highly variable in acoustic character, with zones of high and low amplitude and generally a poor penetration depth (Table 6.1). The sea bed morphology reveals both erosional features down-cutting into the substrate and depositional features co-existing (Fig. 4.2 B). The upper slope shows a smooth, moderate amplitude sea floor reflector with simple parallel bedding which is interpreted as a plastered drift (Table 6.1) and appears to be predominantly depositional in nature.

6.2.1.2 Algarve Margin

Using seismic stratigraphic analysis, this study identifies four key successions within the Pliocene to Lowermost Quaternary section along the Algarve Margin (Fig. 4.5). These have been attributed to the changing dominance of along- and downslope processes leading to the eventual evolution of a contourite depositional system. Seismic unit development is determined by the interplay of the Mediterranean Outflow Water (MOW), tectonic activity and glacio-eustatic sea level changes. Llave et al. (2011) have expressed these sequences as contourite evolutionary stages and interpret the Lower Pliocene as a pre-contourite phase, the Upper Pliocene as an early contourite phase and the Quaternary as a late and contourite-dominant phase. The evidence from this study supports this regional interpretation.

In addition, a mixed system with associated contourite sheeted drift has been identified here for the first time in the Pliocene with downslope and alongslope processes interacting. The region therefore provides a good opportunity to analyse the differing acoustic responses of the sediments deposited by these processes in a buried system where seismic resolution is insufficient to visualise the subtle depositional features (such as those observed on the eastern Gulf of Cadiz data-sets). Conclusions will be made to better identify bottom current reworked sands and sheeted contourite drifts elsewhere in the subsurface.

6.2.1.2.1 Upper Miocene

A considerable thickness of Miocene and older sediments underlay the Gulf of Cadiz contourite system. It is most likely composed of sediments of hemipelagic and turbiditic origin, although transparent seismofacies close to the continental shelf are interpreted as debrite deposits (Riaza and Marínez Del Olmo 1996; Roque 2007; Llave et al. 2011). Deposition of the Cadiz Allochthonous Unit (Medialdea et al. 2004) throughout the Miocene resulted in a complex array of depositional basins and tectonic highs. Neotectonism has since punctured the sediments in some regions, most notably in the east of the study area, and has affected the evolution of the overlying sequences.

6.2.1.2.2 Seismic unit P1; Lowermost Pliocene

The lowermost discontinuity to be interpreted, Discontinuity M (Fig. 3.4; Fig. 4.5) is defined by a change in acoustic response, and acts as a clear onlap surface, especially where the overlying seismic unit P1 appears to 'infill' the Miocene palaeotopography (Fig. 4.5). Locally, there is some evidence of erosion that could indicate some short hiatus associated to Discontinuity M. Overall, the discontinuity has been interpreted as an important change in depositional processes. The overlying P1 sequence is highly reflective and made up of laterally extensive parallel seismic reflections up to 0.15 ms TWT in thickness. The distribution map of this sequence shows a main depocentre in the NE of the study area (Fig. 4.6; 6.2).

The isochon map for the seismic unit P1 shows sedimentation focused broadly in an alongslope orientation with lobes fanning out to the southwest (Fig.4.6 P1). Careful reconstruction of the regional palaeogeography in the Gulf of Cadiz gives clues to the likely origin of this seismic unit. It is known that throughout the latest Miocene a downslope system was supplying the Gulf of Cadiz with sediment from the northeast. The late Miocene / Early

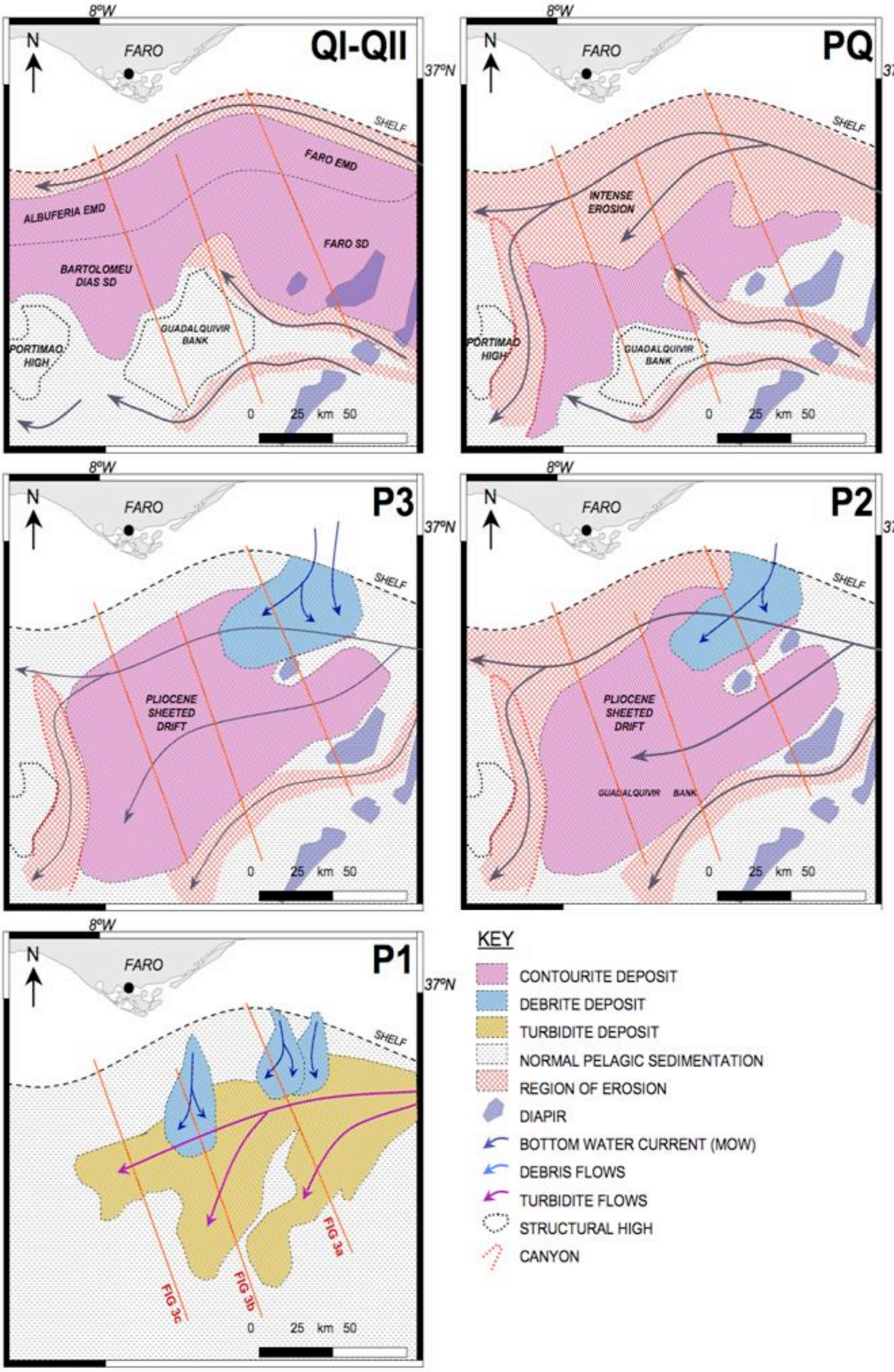


Figure 6.2: Gross depositional environment reconstructions across the study area for depositional sequences P1-QII. It is seen that there is a move from downslope-dominated to contourite-dominated sedimentation. The highly erosive nature of the bottom currents is clear to see along the upper slope and contourite channels.

Pliocene saw an influx of clastic sedimentation across the northeast Gulf of Cadiz and resulted in the deposition of the Guadiana Sands via downslope (most likely turbiditic) processes (Riaza and Marínez Del Olmo 1996). These sands have been identified in industry boreholes to the east of the study area. Based on this, and the distribution trends observed in the data, we can expect that P1 is a distal confined turbiditic fan system, moving along the continental slope and being deflected basinwards (Fig. 6.2 P1). Systems with such a distribution have been observed in the Peïra Cava turbidite system (McCaffrey and Kneller 2001; Amy et al. 2004).

Within the study area, the high amplitude, laterally extensive 'tram line' acoustic response at the base of seismic unit P1 is indicative of sandier facies (although it cannot be quantitatively stated). The seismic facies of unit P1 make it difficult to distinguish along- and downslope deposits, and additional distribution analysis is required to make conclusions on the depositional process.

Locally in regions where the thickness is significant (close to the modern upper slope), complex relationships can be seen in the form of localised onlap relationships (Fig. 6.3). The proximity to the upper slope suggests that two previously unidentified downslope sedimentary systems were feeding this area – one minor downslope system sourcing from the north and a large-scale downslope system sourcing from the northeast, which quickly dominated margin deposition (Fig. 6.2 P1).

The Miocene-Pliocene boundary is generally accepted to be the time when the Gibraltar Gateway was opened, and the subsequent flooding of the Mediterranean ended the Messinian Salinity Crisis (Hsü et al. 1973). However, there is much more ambiguity over when bottom water generation in the Mediterranean Sea reinitiated and the MOW was reinstated in the Gulf of Cadiz. The seismic in the present study shows little evidence of alongslope processes in the lowermost Pliocene. This is in agreement with interpretations from Llave et al. (2011) and Roque et al. (2012). Therefore, if exchange of water masses was occurring through the Gibraltar Gateway at this time, they were insufficient to dominate margin deposition at a seismic scale.

6.2.1.2.3 Seismic unit P2; Late-Lower Pliocene

The Lower Pliocene discontinuity (LPR), located at the base of seismic unit P2, signifies the clear onset (at seismic scale) of the MOW's influence on the study area. This occurred sometime in the Late-Early Pliocene (possibly Late Zanclean) when the Gibraltar Gateway allowed for the exchange of water masses between the Atlantic Ocean and the Mediterranean Sea. Such an oceanographic reorganisation would have had a substantial effect on the depositional style of the margin.

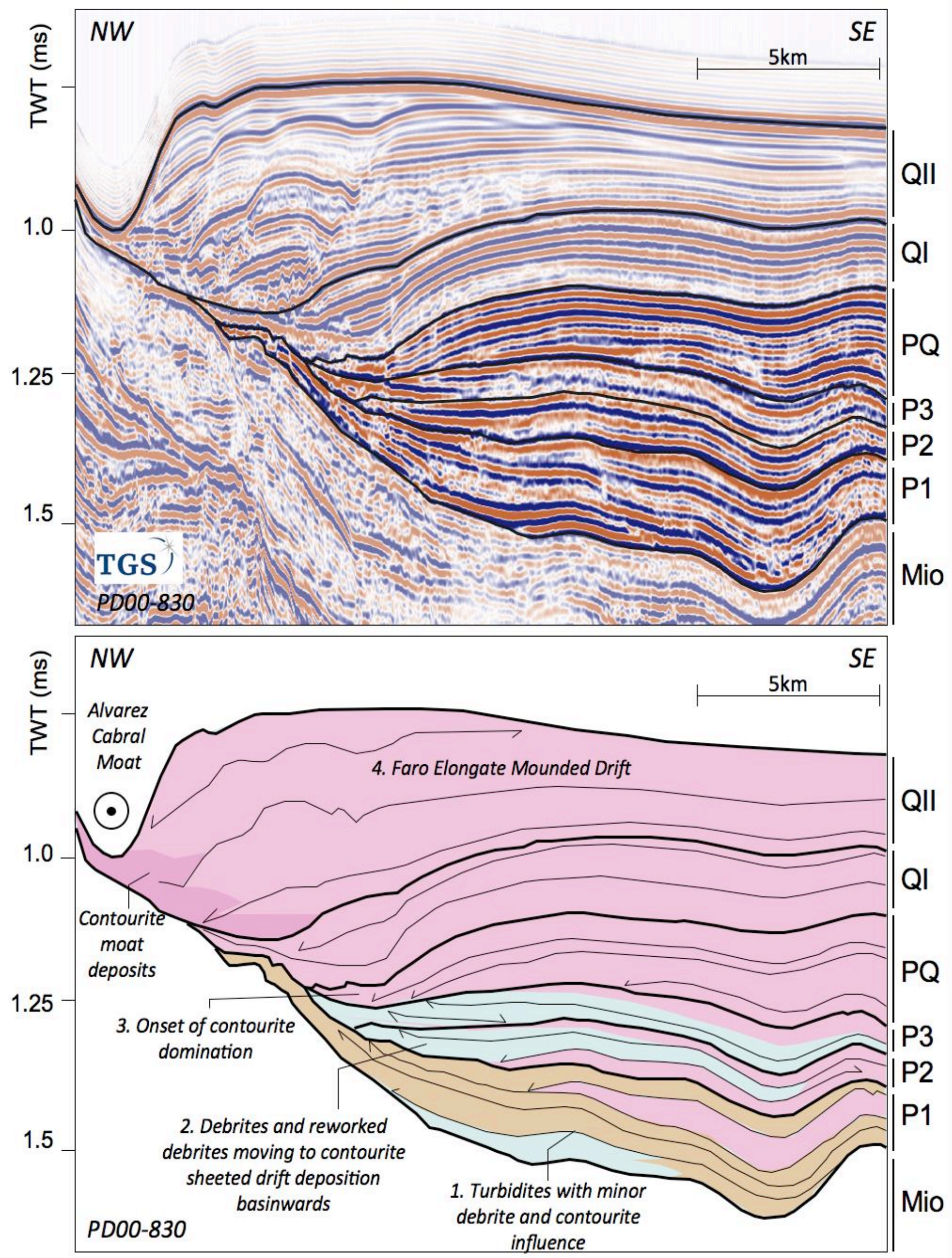


Figure 6.3: Detailed seismic section from line PD00-830 (Fig. 4.5 B). Onlap and truncation trends can be seen in the reflections. Different seismofacies can clearly be identified, most notably, transparent and chaotic in the Pliocene section close to the slope moving to more laterally continuous reflections in the Quaternary section.

The overlying package, P2, is highly variable in character across the region and this has been interpreted to be as a result of multiple depositional processes ongoing thorough the Late Zanclean. Figure 6.2 P2 maps the extent of downslope vs. alongslope sediments, interpreted based on their seismic facies, and distribution. A thick succession (0.2 ms TWT) of chaotic seismic facies in the easternmost study area is interpreted as a downslope mass transport deposit accumulation. Its close proximity to the upper slope suggests debris flow deposits (debrites). Basinwards and westwards, these chaotic facies become increasingly interbedded with more laterally continuous seismic reflections, interpreted to be a Lower Pliocene *sheeted contourite drift* based on its overall regional geometry and high amplitude response. Evidence for contouritic origin for P2 includes: 1) progradation of seismic units upslope, a characteristic commonly used as an identification criteria in many contourite depositional systems (Faugères et al. 1999); 2) an alongslope orientation; and 3) evidence for a highly cyclic nature to the sequence.

6.2.1.2.4 Seismic unit P3; Upper Pliocene

One of the most subtle of the discontinuities along the Algarve margin, the Upper Pliocene discontinuity (UPR) marks a change in sediment acoustic response with a move from high amplitude to semi-transparent seismic facies. The overlying Upper Pliocene sequence shows localised areas of high amplitude reflections, but laterally these give way to semi-transparent regions showing poor continuity. In the NE of the study area, chaotic seismic facies still dominate indicating that in this region a downslope debrite system was still active at this time (Fig. 6.2 P3).

The distribution of the seismic unit shows a largely sheeted morphology, orientated, but thinning alongslope (Fig. 4.6). This observation, combined with the semi-transparent seismic facies, leads to the conclusion that a homogeneous muddy-sheeted contourite drift was deposited at this time, influenced by a relatively sluggish MOW. In addition, there is evidence that there was significant tectonic movement at this time, with P3 thinning considerable over the diapiric ridges and onlapping of seismic reflections onto the underlying UPR discontinuity. This tectonic stress can explain the local occurrence of high amplitude reflections, where diapir growth has affected bottom water flow and locally intensified it, resulting in small patch drifts of coarser material (Fig. 4.5 C) In the northwest of the study area there is still strong interbedding of downslope (chaotic) and alongslope (parallel) seismic facies (Fig. 6.3 P3) indicating that at this time, contourite deposition was not completely dominant along the margin, but a mixed system occurred in the northwest.

6.2.1.2.5 Seismic unit PQ: Uppermost Pliocene - Lowermost Quaternary

The Base Quaternary Discontinuity (BQD) marks a major change in the depositional style of the margin. Throughout the Pliocene, deposition was focused to the east of the study area. This shifts westwards above the BQD. This seismic unit is completely absent from the north of the study area due to intense erosion along the midslope. Only a 'window' into the sequence is preserved basinwards (Fig. 4.5 A; Fig. 6.2 PQ) and therefore it is difficult to be 100% certain of its complete interpretation. Clues to the origin of this sequence can however be gathered. A major change in the system is evident - with an increase in seismic amplitude and a move to discontinuities that are highly erosive in nature. These are characteristics of a high-energy contourite system. Thinning over the diapiric ridges in the east implies ongoing halokinesis, further intensifying the MOW at this time. As erosion dominated in the east of the study area (where reflection truncations are common in the unit), the west was a region of contourite deposition, where the erosive capacity of the bottom current fell as it exited the diapiric ridge province. Here, upslope progradation is evident: a feature common to contourite drift growth (Fig. 6.3) (Faugères et al. 1999).

Due to the absence of the seismic unit in the north of the study area, conclusions cannot be made of the regional drift type as the external and internal morphologies cannot be clearly analysed. What is clear is that the Pliocene-Quaternary boundary was marked by a major period of repeated MOW intensifications and that the ongoing diapiric movements were likely to be instrumental in the change to a contourite dominated system.

6.2.1.2.6 Quaternary

After a period of intense erosion in the lowermost Quaternary, the modern set-up of the margin truly began to establish itself (Fig. 6.2 QI-QII). It is at this time that the contourite system in the study area moves from a sheeted (aggradational) drift to a remarkable mounded elongated and separated drift (progradational and aggradational) (Fig. 6.3). This sedimentary record has been studied in great detail by Llave et al. (2007c) and Roque et al. (2012) among others and is outside the scope of this research. However, it forms a good contrast to the underlying Pliocene sheeted drifts with contourite-turbidite mixed system, and the modern day sandy contourite depositional system in the eastern Gulf of Cadiz. It is separated from the Pliocene sheeted drift system by major discontinuities coeval with tectonic readjustment of the margin. The mounded drift shows the development of a well-formed contourite moat along the midslope, and all the features outlined by (Faugères et al. 1999) as being characteristic of contourite drifts such as upslope progradation and regional unconformities or erosional surfaces.

6.2.2 Sedimentary Analysis

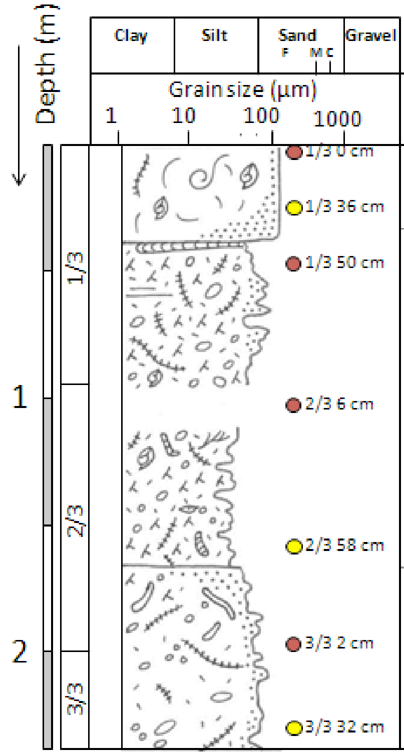
The main focus area of the sedimentary data-sets is the 'proximal scour and ribbons sector' as defined by Hernández-Molina et al. (2006). It is evident from the analysis of the sediment that there are a variety of depositional environments across the study area. Each core has been interpreted (Fig. 6.4) and a justification is given below that utilises evidence from sediment, compositional and facies analysis with acoustic data, to make conclusions on depositional processes and evolution through time at each core site.

6.2.2.1 PC06

Located at 390 m water depth (39,305°N, 6,764°E), piston core PC06 is the shallowest of the cores used in this study. It is located upslope of the northern channel and upper terrace identified by Hernández-Molina et al. (2014). It is sand-rich, and suffers from low recovery as a result at just 2.40 m (Table 3.2). Three distinct units have been identified that are separated by erosional surfaces (Fig. 6.4 A).

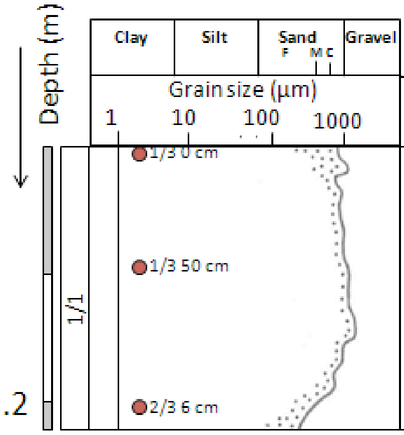
The oceanographic data shows evidence that the MOW is currently affecting this core site. Publically available CTD (Conductivity Temperature Depth) data (Schlitzer 2013) (Fig. 4.3) shows salinity values of 37 ‰ measured close to the core site, an exceptionally high value that is representative of the MOW Upper Water. This is supported in the data-set here by high portions of redox-sensitive minerals which indicate the presence of well-oxygenated bottom waters (Fig. 5.11). The core site is located at the upper slope edge of the Upper Core (MU) of the MOW (Hernández-Molina et al. 2014). Deposition dominates, although minor erosional features and surfaces seen on the seismic data indicate that there have been periods of enhanced and waning bottom current velocity over time in this region (Fig. 4.3). Now however, deposition is dominant, and therefore this core site can be said to be located on a contourite drift. Based on the morphology of the drift identified on seismic data located on the upper slope (Fig. 4.3 A), and the alongslope elongate identified in the bathymetric data, this can be named a *plastered contourite drift*.

A) PC06



Description	Interpretation
Mod sorted poorly consolidated sand. Terrigenous with some shell fragments/microfossils	**Winnowed shelf-spillover deposits** influenced by vigorous bottom water currents.
Very heavily bioturbated, leading to very poor sorting and complex grading. Significant sand portion, with bimodal muds. Mixed composition, with some shell fragments / microfossils (particularly sponge section and spines).	**Contourite plastered drift** influenced by moderate bottom water currents that lead to minor winnowing and enhance bioturbation.
Massive sand (75%) –dominated Bioturbation leading to poor sorting. Largely terrigenous (Quartz) with some large shell fragments and minor biogenic material.	**Winnowed shelf-spillover deposits** influenced by moderate to vigorous bottom water currents.

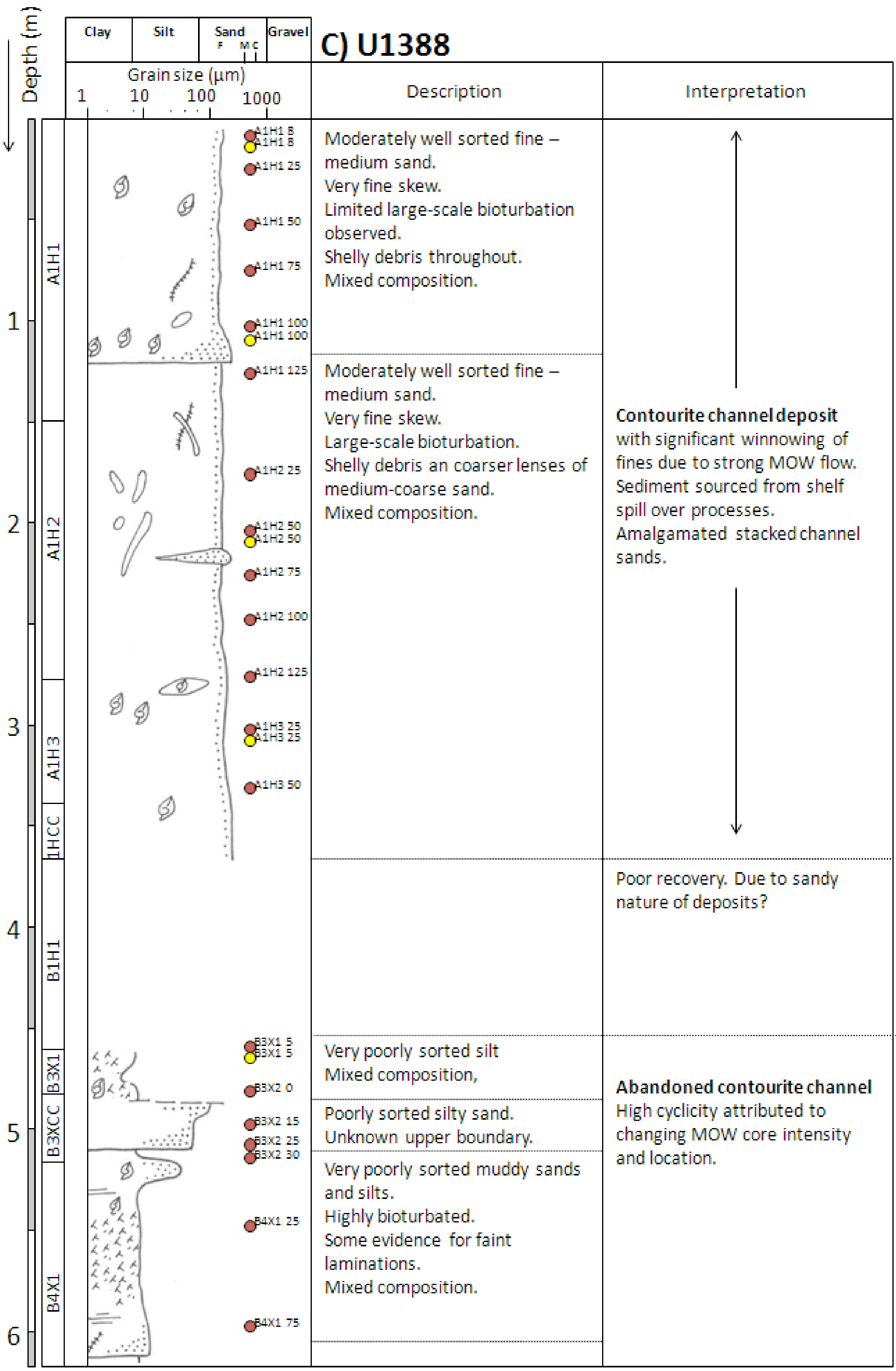
B) BC05



Description	Interpretation
Coarse sand deposit of moderate sorting. Mixed composition and very coarse skew.	**Contourite channel deposit** with significant winnowing of fines.

Note the modified vertical scale for BC05

Figure 6.4 continued overleaf



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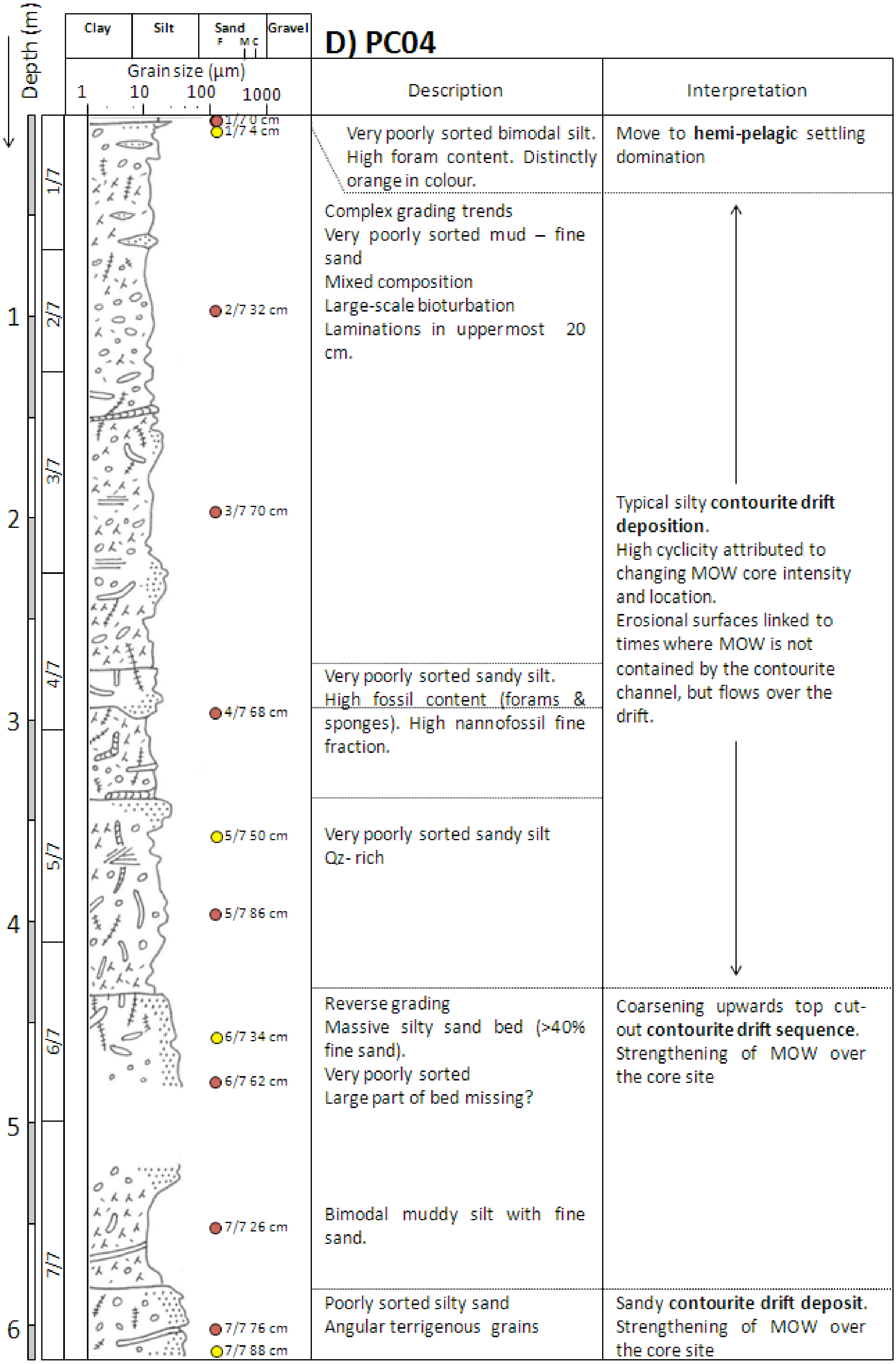

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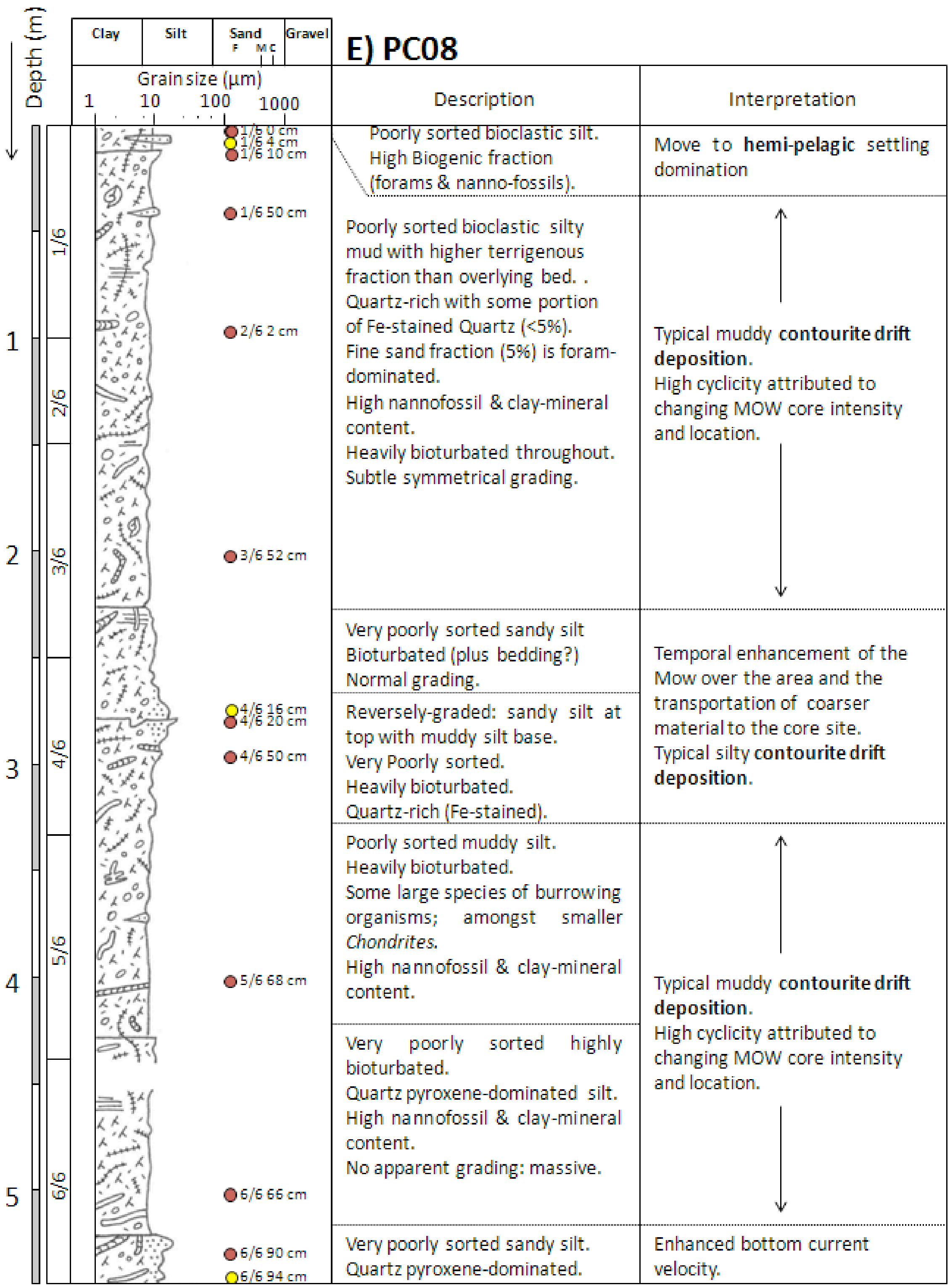

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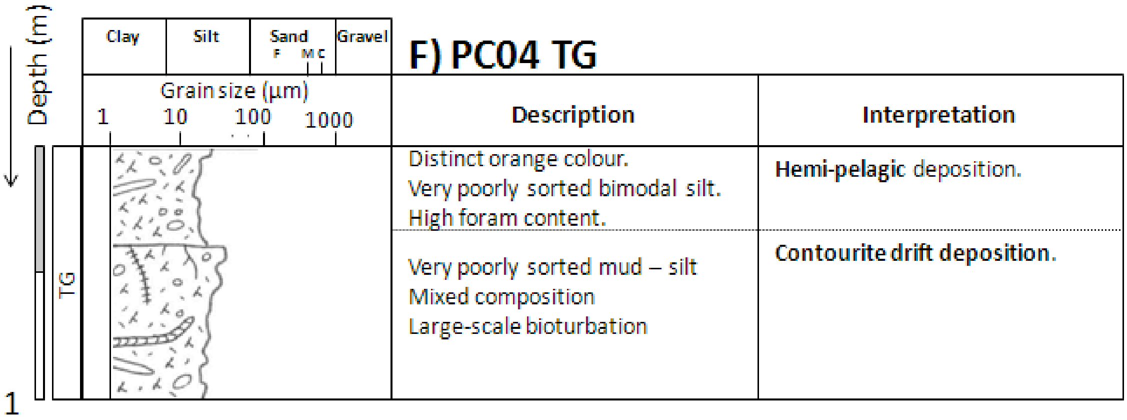

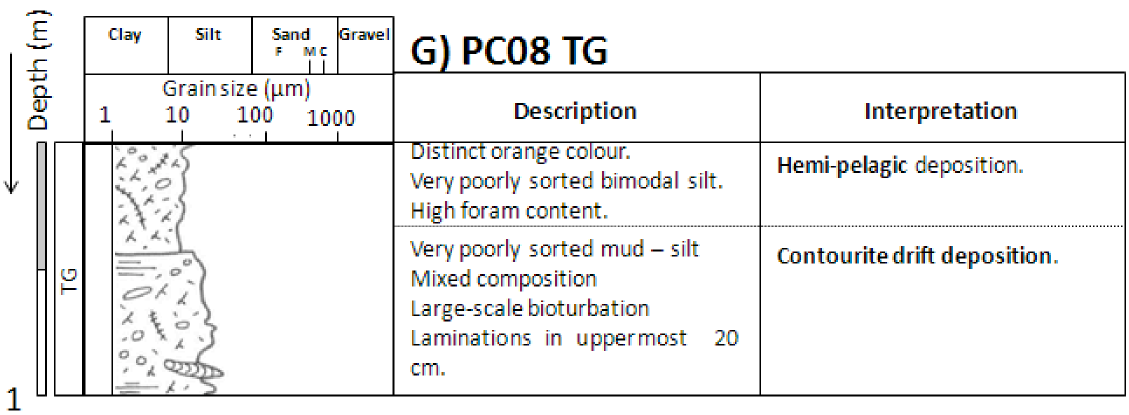

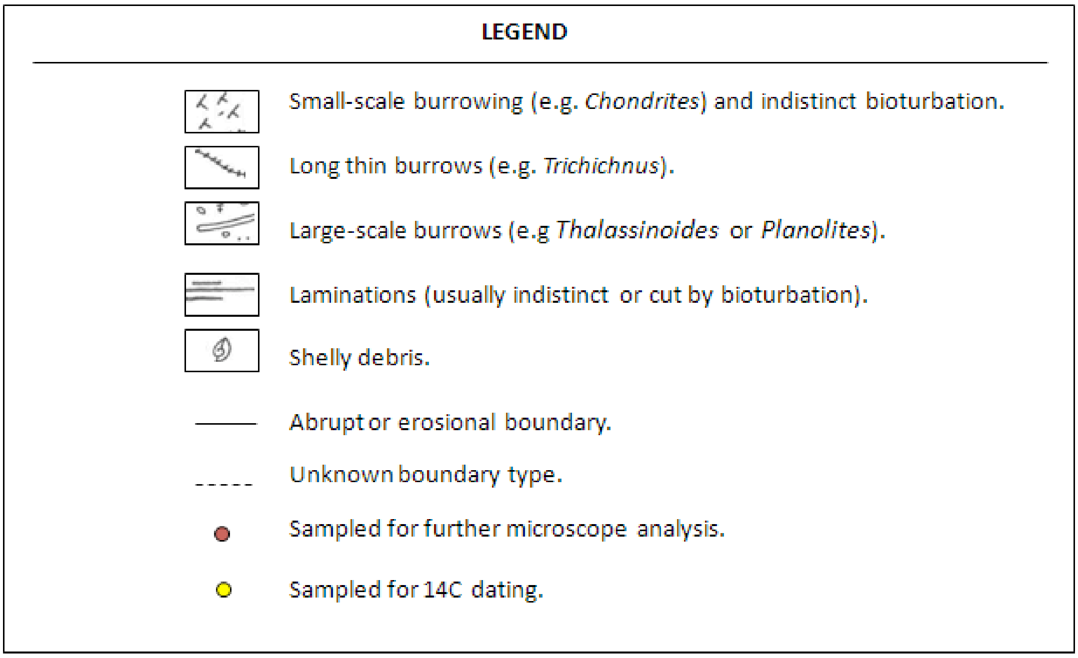

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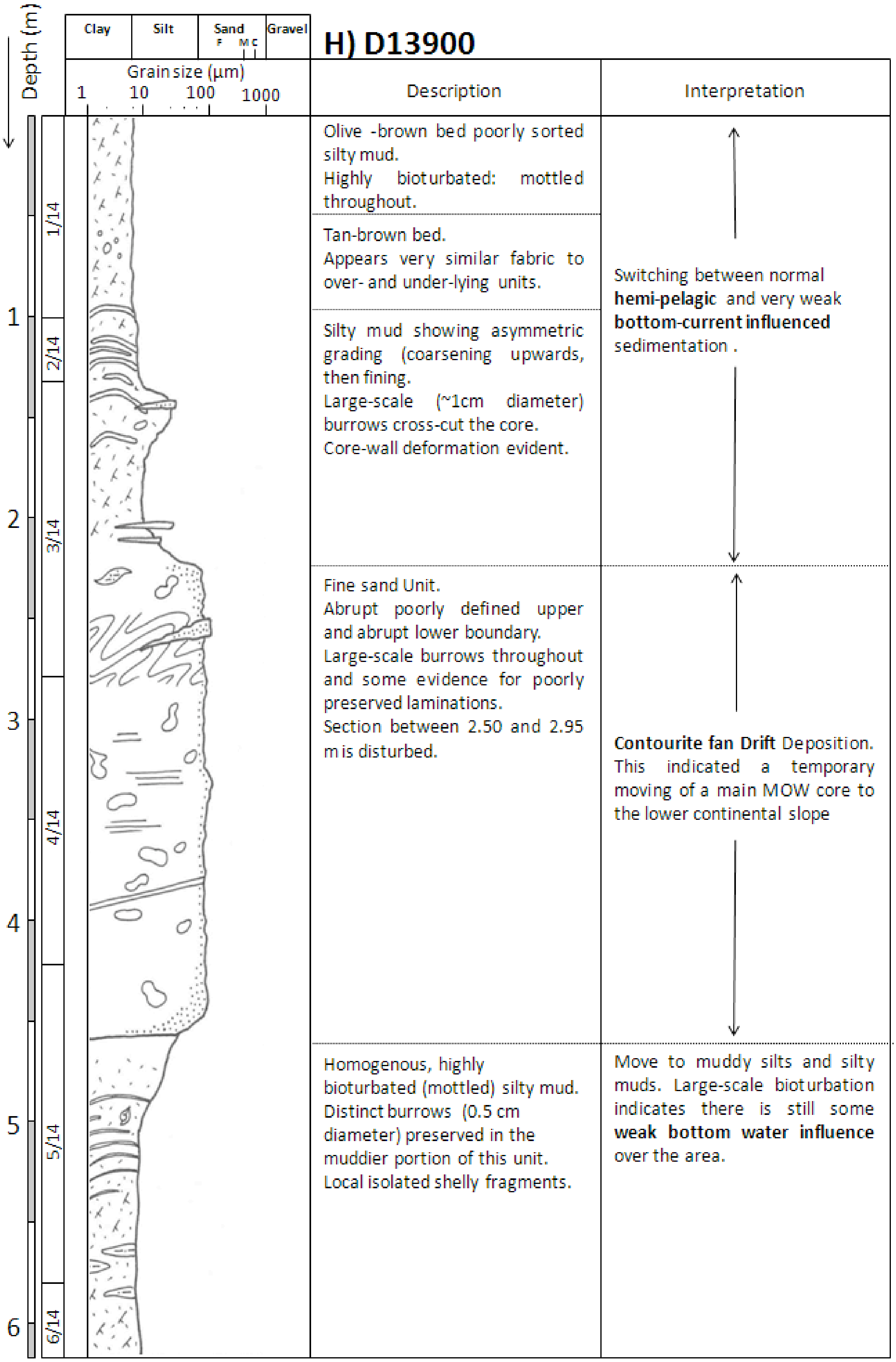


Figure 6.4: Final logs and interpretations from the core sites. A) PC06; B) BC05; C) U1388; D) PC04; E) PC08; F) PC04 Trigger Core; G) PC08 Trigger Core: H) D13900.

At a sediment scale, three units have been identified (Fig. 5.14; 6.4 A) the differences between units allow us to conclude that changing depositional controls are temporarily seen over this core site. The topmost unit, the coarsest and best sorted (Fig. 6.5), can be linked to the present-day CTD observations. It is clearly influenced by the MOW with sufficient velocity that fine sands are deposited. Unfortunately, the unit was heavily disturbed during core acquisition, and no sedimentary features (structures or bioturbation) have been preserved. This distribution has also made ^{14}C dating of this unit impossible and so no accumulation rate is calculated. However, based on the mean accumulation rate of the entire core, it is expected to be moderately high (the lower sand unit is comparable is facies and reaches 68 cm/ka). For fine sand to be deposited, bottom current velocities of around 0.2-0.4 ms^{-1} are expected (Stow et al. 2009). The sediment is composed of dominantly terrigenous material (up to 40% quartz content), and there is a considerable amount of large (cm-scale) shelly clasts. This high shelly debris content is in line with the XRF data that shows a high calcium (Ca) content (Fig. 5.10). It is concluded here, therefore, that unit 1 is made up of sediments that are locally derived from the continental shelf and have been modified and cleaned by intense bottom current (MOW) action (Fig. 6.4 A).

Units 2 and 3 show features that are thought to represent plastered contourite drift sediments. Unit 2 is finer and very poorly sorted (Fig. 6.5). Heavily bioturbated, the facies are typical of muddy silt contourite facies. Compositionally it is very different from the overlying unit 1 with a unique trend on the compositional cross plot of Figure 6.6 C. As a result, it can be concluded that unit 2 is probably sourced from a different sediment provenance than overlying unit 1. The lack of sand-sized grains indicates a temporary reduction in sand influx and possibly a more alongslope sourced sediment provenance. The unit shows a moderate accumulation rate (28.57 cm/ka) and is interpreted as a typical muddy- to silty- plastered drift deposit (Fig. 6.4 A). Heavy bioturbation has led to some mixing between units 2 and 3 as evidenced in the compositional data. The underlying unit 3 is visually more similar to the topmost unit, however is more poorly sorted and has a finer average grain size. There is also more evidence for some deep-reaching burrows, and a smaller quartz portion. All this evidence allows us to conclude that unit 3 is again a contourite drift deposit with bottom current reworking and winnowing of some additional local sediment influx from the shelf (Fig. 6.4 A).

All the data (acoustic and sedimentary) show that at the core site location PC06, a contourite plastered drift has developed. However, careful examination of the sedimentary units show that at times, downslope sediment supply (probably derived locally from the shelf) dominated the system and forms interbedded re-worked units.

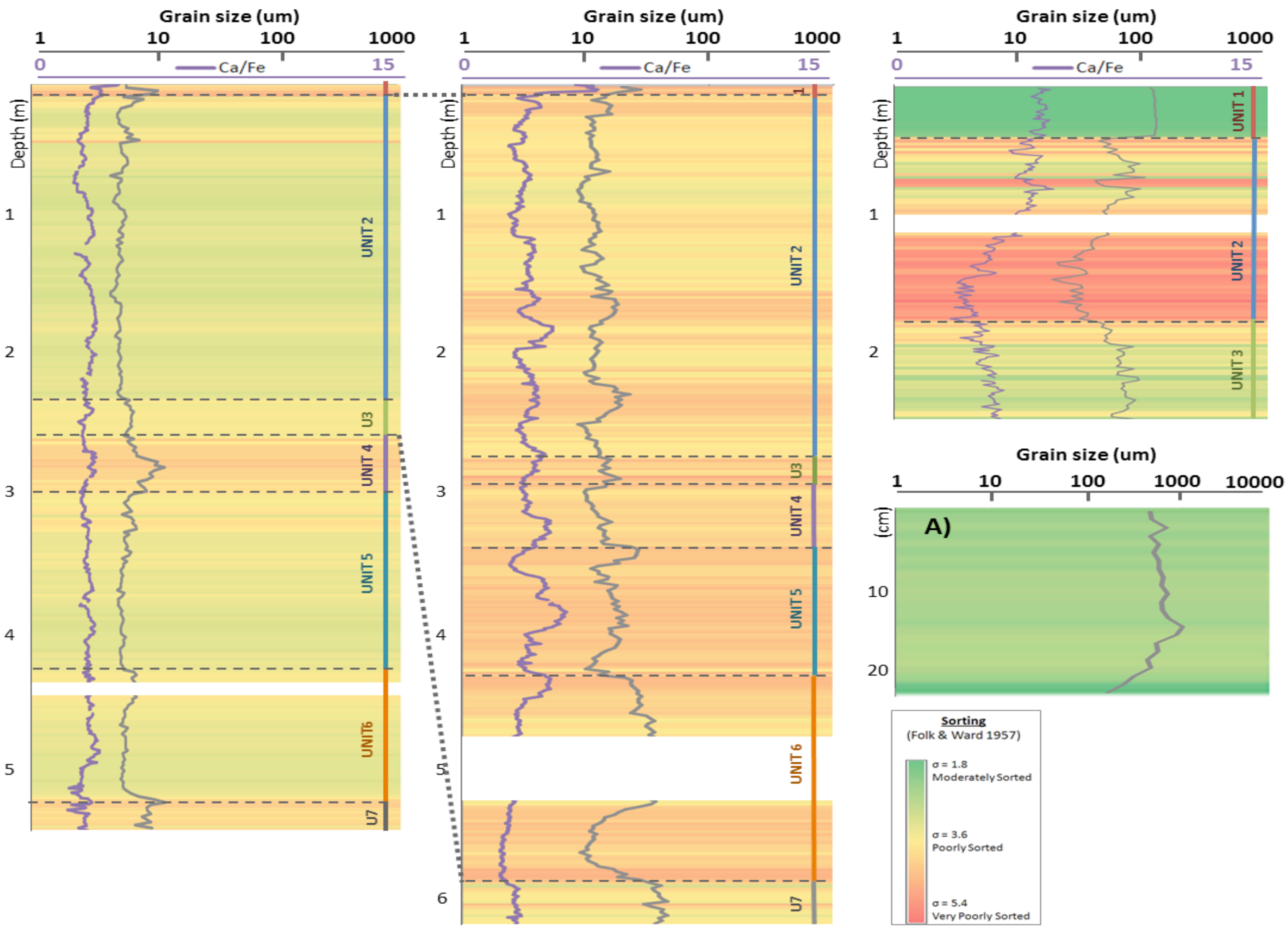


Figure 6.5: Sorting plotted with grain size (black curve) and Ca/Fe (purple curve). Note the change in scales for BC05.

6.2.2.2 U1388

Collected on the IODP 339 Expedition, core site U1388 is located very close to PC06, located just downslope at 663 m water depth on the midslope terrace (36,255°N, 6,476°E). The core site is located within the northern channel defined by (Hernández-Molina et al. 2014) (Fig. 4.3).

The sediments in U1388 are interpreted as *contourite channel* sand deposits (Fig. 6.4 C). Evidence from seismic and CTD data (Fig. 4.3) show that the upper core of the MOW is largely confined to the alongslope orientated contourite channel and is pushed against the upper channel margin (due to Coriolis Forces). The modern sea floor appears highly erosive in seismic and multibeam bathymetry (Hernández-Molina et al. 2014), with a rough sea bed and erosional truncation of seismic reflections on the upslope side of the channel (Fig. 4.3 A). Within the channel itself, the acoustic facies are chaotic and of low amplitude. All this suggests a vigorous upper branch of the MOW presently acting at this core site and the presence of sandy sediment within the channel.

Although not sampled and analysed as extensively as the other sediment cores in the study, some good conclusions can be made about the depositional environment at core site U1388 based on preliminary grain size analysis of 18 samples from the top six metres of core (Fig. 6.4 C) (Llave et al. 2014). The upper 3.5 metres of this core consists of moderately sorted medium sands with a very fine skewed to symmetrical grain size distribution. This uppermost section is divided into two units based on an erosional surface at 1.4 m. These amalgamated sands show high levels of reworking that have affected the ^{14}C dates. Despite this, high accumulation rates are estimated in the region of 100 cm/ka (Fig. 5.23). The sands are interpreted to be contourite channel deposits from which the grains that are sized up to approximately 63 µm (muds and silts) are transported further down current by the MOW, leaving clean sands along the channel axis. There is no compositional data for core site U1388, however, the bathymetry data shows downslope-orientated gullies across the upper slope incising the plastered drift above the channel (Fig. 2.7) (Hernández-Molina et al. 2014). These could act as important conduits for the supply of sandy material into the system.

Poor recovery rates have led to a missing section directly below the sandy facies (Stow et al. 2013a), below which a further three units have been identified (Fig. 6.4 C) dated to Late Pleistocene (Fig.5.22). These units have very different characteristics from the upper section of the core. The grain size is much more varied, with muddy, silty and sandy layers. Boundaries are erosional or gradational. Overall, the facies represent a much reduced velocity of the MOW over the core site pre-Holocene with high cyclicity being linked to periodic strengthening of the MOW mixed with sediment influx from the upper slope and shelf.

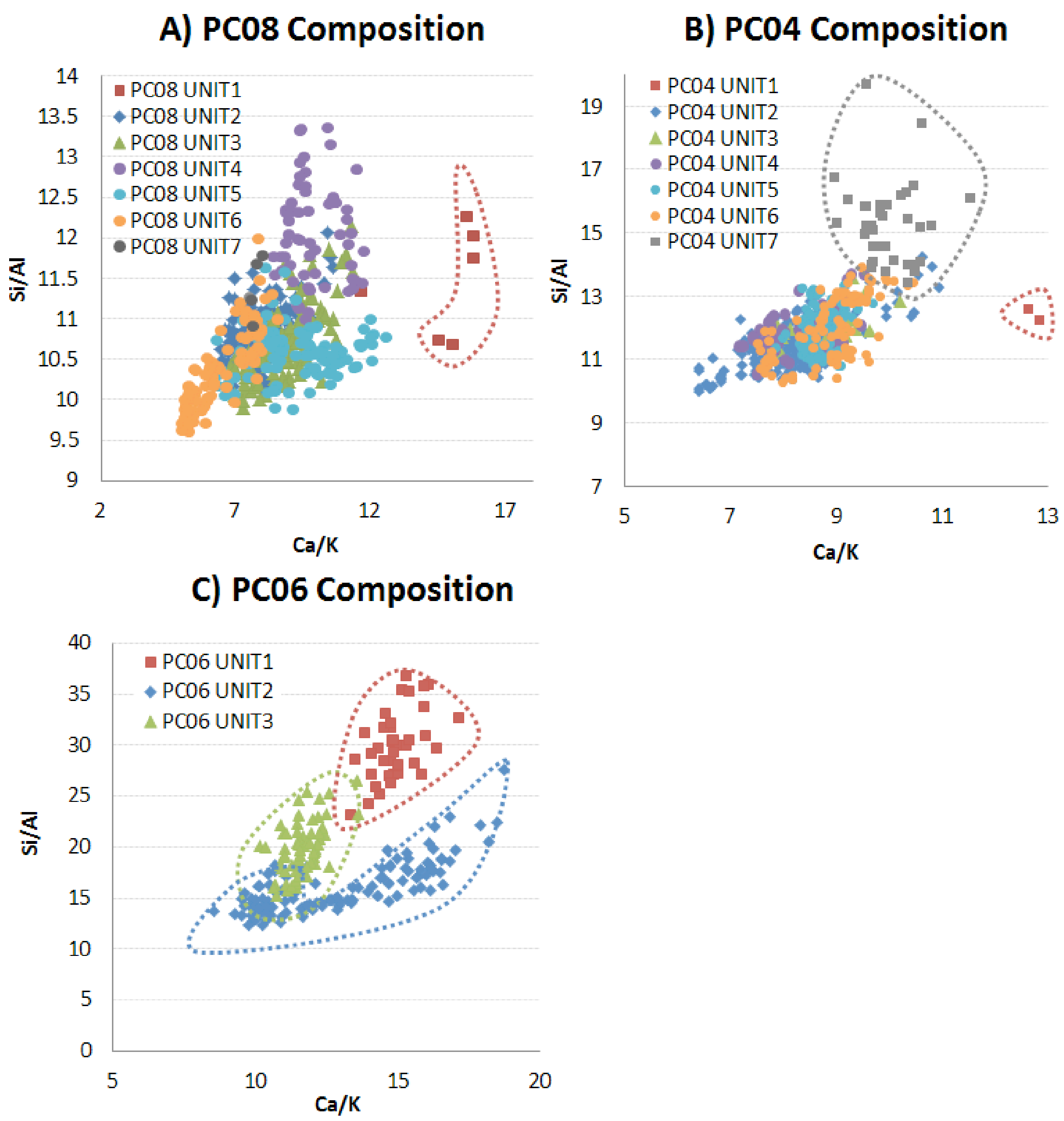


Figure 6.6: Composition cross plots for the three piston cores, as plotted by sedimentary unit. Unit are shown in Figure 5.14.

6.2.2.3 BC05

A box core recovered from the southern channel defined by Hernández-Molina et al. (2014) is located along the midslope contourite terrace and provides the coarsest sands collected in this study. Located at 35,846°N, 6,780°E in 738 metres water depth (Table 3.2), 24 cm of core was collected and sub-sampled in 1 cm intervals. Although no core slabbing analysis was carried out (logging, XRF, CT-imaging), the grain size analysis and acoustic data give clues to the origin of this sediment as discussed below.

The sediments in BC05 are interpreted as a *contourite channel* sand deposit (Fig. 6.4 B). Evidence from seismic and CTD data show that the lower core (ML) of the MOW is confined to the alongslope orientated southern channel (Hernández-Molina et al. 2014). The modern sea floor appears highly erosive in seismic, with a rough sea bed and erosional truncation of seismic reflections on both sides of the channel (Fig. 4.3). Only 23 cm of sediment was collected, however the seismic facies analysis shows that similar deposits would be expected deeper in the subsurface. Cyclicity is evident and large wide-spread erosional surfaces are also seen. Hernández-Molina et al. (2014) suggest that the lower core of the MOW is more active within this channel during glacial climatic periods, which may result in this cyclicity in the seismic data. There are underlying extensional faults imaged in the seismic which, although not presently reaching the sea floor, may have controlled the placement of the contourite channel and forced the capture of the MOW (Fig. 4.3).

Grain size analysis shows the BC05 sediment is gravelly sand by texture (> 97 % sand) and poorly to moderately sorted (Fig. 6.5). Its key sedimentary characteristic that distinguishes it from the other core sites is it coarse- to very coarse skew (Fig. 5.16 B) that is interpreted to represent a MOW velocity capable of winnowing away any finer sediment. Compositionally, the coarsest portion is made up of large bioclastic clasts (shelly material). Therefore, some element of downslope sediment influx is required. Bathymetric data shows no obvious conduits for downslope sediment supply to this core site (Hernández-Molina et al. 2014), and therefore a source from closer to the Gibraltar Gateway supply is tentatively proposed.

6.2.2.4 PC04

Located adjacent and downslope of BC05 is core site PC04. At 658 metres water depth, it sits above BC05 on a large mounded contourite drift at 35,737°N, 6,732°E (Fig. 4.3 B). A total of 6.22 m of sediment was collected in the piston core with an additional 1 metre being collected from the trigger core (Table 3.2). The topmost 50 cm appears to be absent from the piston core, but can be correlated across to the trigger (Fig. 5.5).

The sediments from PC04 show all the characteristics of a silty contourite deposit. Additional information from seismic data allows us to interpret this as an el*ongate mounded contourite drift* (Fig. 6.4 D). The oceanographic data shows that the MOW lower branch (ML) is currently fully contained by the deep channel and does not affect the core site (Fig. 4.3). However, heavy mineral indicators from the XRF data (used to identify times of enhanced bottom currents) show a significant high in the lowermost section of the core (Fig. 5.12) indicating enhanced ML influence in the past. The mounded drift is covered by a sedimentary wave field (Fig. 4.2) and deposition is the dominant process. It appears that sedimentary waves have been found on this drift throughout its evolution, although temporarily enhanced bottom currents have locally eroded the drift. Going further back in time, it is clear that the mounded drift accumulation has been periodically ‘switched off’ and replaced by an erosional contourite terrace-like morphology. This is evidenced in laterally continuous erosional surfaces that are seaward dipping and form onlap surfaces (Fig. 4.3).

The sediment facies are typically contouritic with elevated bioturbation rates, gradational facies boundaries and bigradational grading. High cyclicity is noted at this core site (<0.5 m), which shows the highest frequency of grain size changes of any of the sites in this study. As a result, seven units have been identified based on major erosional boundaries, compositional variations, and changing facies (Fig. 6.4 D; Fig. 6.5). The uppermost unit shows a different compositional make-up from all the underlying units which may be related to the lack of present day MOW influence. Unit 1 (largely seen only in the trigger core) contains a large foraminifera content and XRF analysis shows high Ca ratios. This is thought to represent a domination of hemipelagic deposition.

Units 2-6 show characteristically contourite facies dominated by very poorly sorted sandy mud facies. There are, however, both gradational and erosional changes towards sandy silts, inferred to be related to periodic enhancement of the MOW over the core site. Facies sequences tend to be asymmetric or top-cut-out. The lowermost units 6 and 7 show some very different sedimentological characteristics compared to the overlying units. They consist of two fine sand packages separated by muddy silts. Only in these units does increased grain size relate to increased sorting. Here, we propose that periodic increasing and strengthening of the MOW (that is currently contained within the lower contourite channel adjacent to the drift) results in some overflowing of both bottom currents and sediment onto the drift top and the deposition of sediment. Compositionally, the sediment is very different to the upper slope core sites PC06 and U1388 (Fig. 6.6) and therefore a different sediment provenance is hypothesised, potentially from sediment pirating off the shelf close to the Strait of Gibraltar with a Mediterranean component. The deep adjacent contourite channel (where BC05 is located) retains much of the coarsest sediment entering this system and a large bottom water core is required to allow coarser sediments to overspill on to the mounded drift. This appears to have happened in the lowermost section of the core (dated Pleistocene) (Fig. 6.7).

Hernández-Molina et al. (2014) note that the contourite features observed at this locality are too large to have been formed by the bottom currents acting here today and suggests that the southern channel and adjacent drift were more active in cold stages. Work by Rogerson et al. (2005; 2012) has proven that the MOW is much more mobile than originally thought. The Overflow is highly sensitive to climatic fluctuations that affect its settling depth. This is in agreement with the calculated accumulation rates at this core site that show an increase from 13.49 to 141.4 cm/ka down the core (Fig. 5.23). This will be discussed further in Section 6.3.2.

6.2.2.5 PC08

PC08 is located at 961 metres water depth (35,8213°N 6,9682°E). It is closely related to core site PC04, located approximately 25 km away on the same contourite drift. 5.36 m of core was collected in the piston core, with an additional metre in the trigger (Fig. 6.4 E; G).

PC08 is the muddiest of all the sediment cores. It does however show small interbedded silty and fine sand layers and subtle erosional surfaces. The sediments from core site PC08 are interpreted as a fine-grained muddy contourite deposit (Fig. 6.4 E). The acoustic data shows that it is located on the same flank of a contourite *elongate mounded drift* as PC04 and the modern day sea floor is dominated by mud waves (Fig. 4.2). Deposition is the dominant process and the parasound clearly images parallel bedding that progrades with the sediment wave (Table 6.1).

As a result of complex sediment wave-generated erosional and progradational units, the correlation of beds between PC08 and PC04 is not strictly possible with the exception of the uppermost unit 1 which is interpreted as a pelagic drape on account of its differing composition compared to the underlying units (Fig. 6.6) and its traceability between cores PC04 and PC08 due to its distinct tan colour. It should be noted that this Unit is largely absent from the piston core, but forms a 50 cm thick unit within the associated trigger core (Fig. 6.4 G). The base of this unit is thought to represent the Holocene-Pleistocene boundary based on the Ca/Fe results which show a sharp reduction on Ca values (Fig. 5.10).

It is clear that bottom currents must have influenced the deposition of the remaining six units identified (Fig. 6.4 E). Poorly sorted silt and mud facies of symmetrical or finely skewed distribution dominate. The core site is located some distance from the Gibraltar Gateway where the MOW is broad and sluggish. Therefore some reworking of hemipelagic sediment could explain the observations (Fig. 6.4 E). Periodic strengthening of the MOW over the core site is the cause of the coarser sediment that is seen (units 3, 4 and 7). Compositional analysis of the sediment with depth reveals and number of different things. Firstly, a cyclic alternation between more siliciclastic and carbonate dominated sedimentation (Fig. 5.10). The resulting trend appears similar to $\delta^{18}O$ signal seen in pelagic and hemipelagic sedimentation across the globe. Rogerson et al. (2005) suggest that this is related to changing domination of microfossil settling during sea level highs vs. clastic influx during sea level lowstand and points towards a hemipelagic-to-muddy contourite sedimentation at this core site.

As with PC04, there is an increasing rate of sediment accumulation down the core from 7.52 cm/ka to 35.5 cm/ka (Fig. 5.23) and a corresponding increase in sand content. This is suggestive of an increased influence of MOW in the past.

6.2.2.6 D13900

Core D13900 is of particular interest on account of the presence of a thick sand unit between ~2.5 and ~4.5 metres (Fig. 6.4 H). It was collected from the lower slope at 1297 m water depth (35,810°N, 7.517°E) making it the deepest of the cores examined in this study.

The sediment at core site D13900 shows evidence for multiple depositional processes over time. The sequence is interpreted as a *contourite fan drift* deposit capped by a *hemipelagic* sequence. With no acoustic data available over the core site for this study, all information was gathered from publications on the area. The morphology of the region is well constrained through bathymetric studies (Mulder et al. 2003; Hanquiez et al. 2007) and studies using seismic data (Habgood et al. 2003; Hanquiez et al. 2010). Located on the lower slope, the core site is situated at the exit of the downslope-orientated Gil Eanes Channel (Kenyon et al. 2000) (Fig. 2.6). This channel incises into the lower slope which appears to be a downslope lateral extension to the mounded drift that core sites PC08 and PC04 are positioned on and is covered in sediment waves.

Detailed sedimentary logging of piston core D13900 reveals five units (Fig. 6.4 H). The muddy uppermost units (1-3) are typical of a very low energy hemipelagic environment. This is backed up by oceanographic (CTD) data that shows the core site is currently below the point that the MOW leaves the sea bed (Hanquiez et al. 2010). Below the MOW, the North Atlantic Deep Water (NADW) flows over the sea bed which, in the Gulf of Cadiz, is expected to form a broad, very sluggish flow. A subtle change in colour between unit 2 and units 1 and 3 is tentatively interpreted as changing depositional process between hemipelagic and very weak reworking by bottom currents. An underlying thick (approximately 2 m) sandy unit shows large-scale bioturbation and some faint evidence for lamination (Fig. 6.4 H). No grading is evident, although there is a region of highly disturbed sediment. This unit has been dated to the marine isotope stages 2-4 by Habgood et al. (2003) and slightly older by Rogerson et al. (2005). Either way, it appears that the sandy unit represents pre-Holocene deposition. It marks an increase in bottom current activity, and the transport of sands to the core site. The final unit at core site D13900, underlying the sandy unit 4, is a silt to siltly-mud that is interpreted as a muddy contourite deposit. This is on account of the large-scale bioturbation and discrete coarse silt lenses representing temporal or spatial zones of enhanced reworking and winnowing. The Gil Eanes Channel connects the midslope to the lower slope and, in the past, must have siphoned a portion of the MOW down to the lower slope. Bottom currents contained by the Gil Eanes channel would have been subject to morphological and gravitational acceleration. They were thus able to transport good quality sand over the 40 km from the midslope contourite terraces. Upon reaching neutral buyonancy, the MOW ceases to accelerate downslope, and therefore its velocity will decrease. This will reduce its erosive capacity, and the channel will terminate. Without a channel to contain the MOW core, the water mass will spread, and further decelerate, dropping its bed load and resulting in the deposition of good quality sands at the channel exit. This is thought to be the depositional process responsible for the sand unit in D13900. However, the accumulation of fine-grained hemipelagic sediments above this sand unit indicates that such processes were acting in the past and are no longer continuing. This has been linked to a denser ML during glacial times (Hernández-Molina et al. 2014; Rogerson et al. 2005). This is further discussed below in section 6.3.

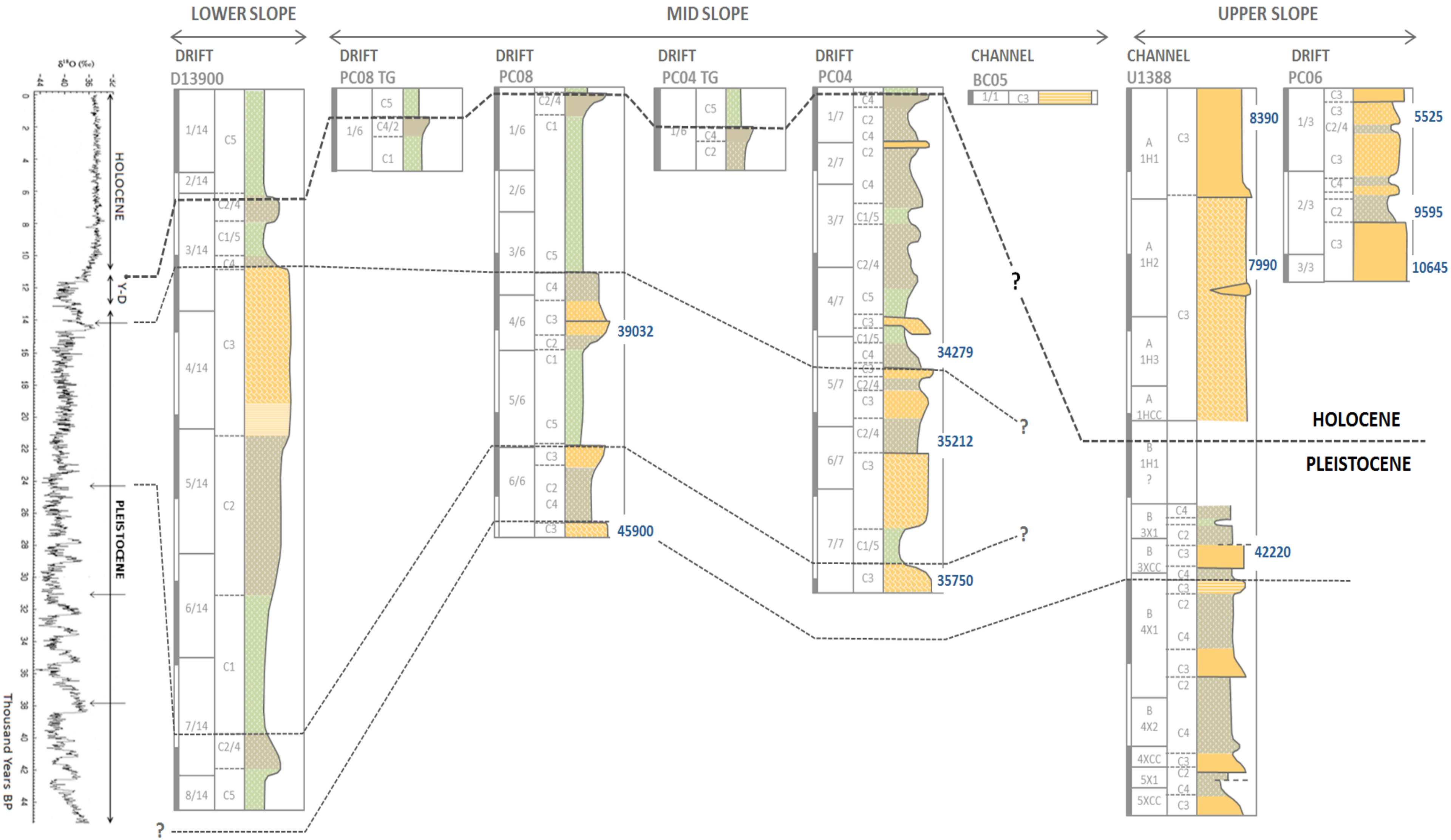
6.2.2.7 Core Correlation

The core data has been used to aid correlation across the core sites. Some beds are easily correlated between core sites by visual inspection of the sediment (e.g. unit 1 is clearly identified in both PC04 and PC08 based on colour alone and can be backed up by compositional data). Other beds require more data for tentative correlations to be made. The study uses a combination of visual core descriptions, compositional data (where available) and sediment dating to place these sediments within a stratigraphic framework. Eight cores were selected for correlation; six from the CONTOURITBER I study (PC04, PC04 TG, BC05, PC06, PC08, PC08 TG), one from the IODP 339 expedition (U1388) and one from the lower slope NERC cores (D13900). These were selected on account of: 1) Their good representation of an upper to lower slope transect (location indicated on Fig. 3.1); and 2) The availability of data. Figure 6.7 gives the final core correlation panel, with the justification outlined below.

6.2.2.7.1 ^{14}C dates

Dates for the sediments across the region have been compiled. Ages were acquired from various sources; the lower slope core D13900 from Rogerson et al. (2005); PC04, BC05, PC06 and PC08 from ^{14}C dating and U1388 from ^{14}C dating and palaeontology studies by The Expedition 339 Scientists (2012).

The Holocene-Pleistocene boundary is fairly well constrained across all core sites (black dashed line Fig. 6.7). A sand unit in core D13900 between 2.5 and ~4.5 metres has been dated to marine isotope stages 2-4 by Habgood et al. (2003) and slightly later by Rogerson et al. (2005), who interprets the overlying mud unit as Holocene in age. Based on the ^{14}C dating, the same can be said for the midslope cores used in this study (PC04, PC08 and their associated trigger cores) – that a muddy Holocene unit caps more rapidly accumulating sediments dated from the Pleistocene. The cores in the mid- and upper-slope have been dated using ^{14}C methods. Final dates are shown in Figure 6.7. A much thicker Holocene section is observed in the upper slope cores when compared to the mid and lower slope.



LOWER SLOPE
MID SLOPE
UPPER SLOPE
DRIFT D13900
DRIFT PC08 TG
DRIFT PC08
DRIFT PC04 TG
DRIFT PC04
CHANNEL BC05
CHANNEL U1388
DRIFT PC06
δ18O (‰)
HOLOCENE
Y-D
PLEISTOCENE
Thousand Years BP
39032
45900
34279
35212
35750
8390
7990
42220
5525
9595
10645
HOLOCENE
PLEISTOCENE

Figure 6.7: (previous page) Core correlation panel form the deepest core (left hand side) to the shallowest (right hand side). $\delta^{18}O$ graph sourced from (Stuiver and Grootes 2000). Ages were acquired from various sources; D13900 and D1389 from Rogerson et al. (2005); PC08, PC06, U1388 and PC06 from ^{14}C dating. The Holocene-Pleistocene boundary is well constrained (black dashed line). Rogerson et al. (2005) tentatively associate sandier facies on the lower slopes with increased glacial activity and calculate rapid shoaling of the MOW during times for deglaciation or Heinrich events. We therefore expect increased sand deposition across the upper slope during interglacial events.

Other events are linked to glacial maxima and Heinrich Events, although the low resolution dating, and the inconsistencies between the ^{14}C dates make these correlations less certain (grey dashed lines of Fig. 6.7). All the sediment found in the core is of Holocene and late Pleistocene in age. They cover the last glacial, the Holocene warming, and 3-4 Heinrich events (Fig. 6.7).

6.2.2.7.2 XRF

Further evidence for correlation was gathered from XRF data in the CONTOURIBER I piston cores (PC08, PC06, and PC08). Chapter 5 outlines the methods and results from the various analyses completed using the raw XRF data. It yielded important information about sediment composition, but is also a useful tool for core correlation.

Firstly, the Ca/Fe results (Fig. 6.8) show very different trends down all three core sites. Having said this, all three cores show an upper unit with high Ca/Fe overlying with an abrupt reduction in values in the underlying unit (Fig. 6.8). This could be tentatively interpreted to be the Holocene-Pleistocene boundary, but ^{14}C dating shows this is not the case in the upper slope PC06 core which is made up of entirely Holocene succession and smear slide analysis links this to increased shelly material content. It is however likely representing the Holocene-Pleistocene boundary in the midslope PC04 and PC08 cores. Examination of the composition of this upper unit (unit 1 in Figure 6.6 A; B) shows that it can be traced between PC08 and PC04, but is very different from PC06 in cross plot (Fig. 6.6). The sudden increase of Ca/Fe values in the upper unit of the piston cores PC08 and PC04 is therefore likely to represent the Pleistocene-Holocene boundary (based on Ca/Fe data and ^{14}C dating). The Holocene-Pleistocene boundary in U1388 appears to be absent (lost during the core acquisition process), but is dated to be below a thick sand accumulation (Fig. 6.7).

Mn is also a good aid to core correlation. In Chapter 5 it was noted that the Mn count was significantly higher than would be expected in deep marine cores elsewhere. The results show some distinct trends down the core that, along with the Ca/Fe curves can be tentatively correlated between PC08 and PC04 with limited success (Fig. 6.8). What is more useful are the Si/Al, Ti/Al and K/Al curves acquired in XRF. Coincident peaks have been used in other studies to identify times in enhanced winnowing (Wehausen and Brumsack 1999). Here they also provide a powerful core correlation tool (Fig. 6.9).

Using all the information, a final core correlation panel has been created. Figure 6.7 shows from the lower slope (left hand side) to the upper slope (right hand side). The δ18O graph sourced from Stuiver and Grootes (2000) and shows the major climatic events that have influenced the Atlantic Ocean. The preliminary conclusions from the core correlation panel are that more sand-dominated deposition occurred across the upper slope during the Holocene, whereas sand was more prevalent in across the lower slope prior to the onset of the Holocene. This will be discussed further below.

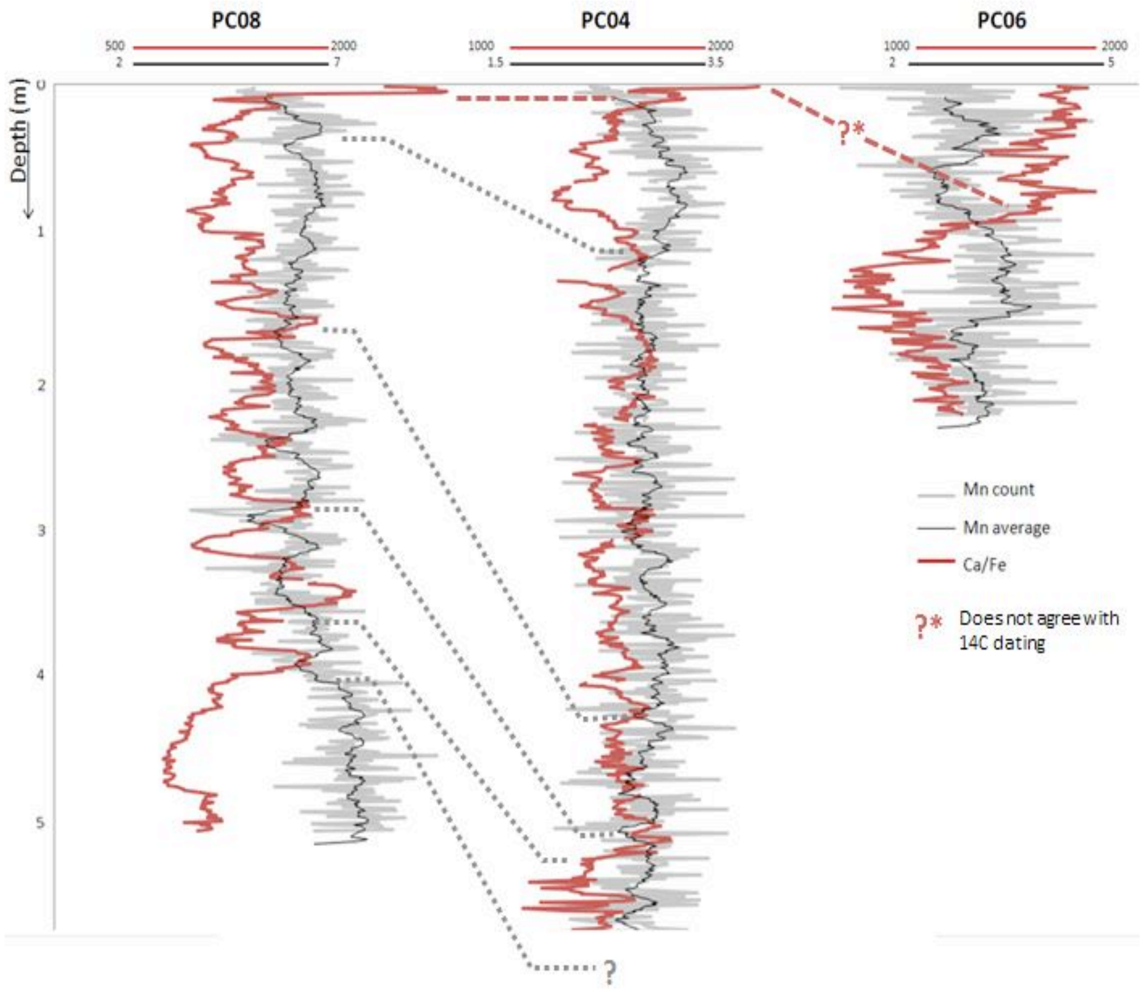


Figure 6.8: Mn/Al curves plotted with Ca/Fe for the three piston cores. High Mn values indicate times when the region was swept by well-oxygenated bottom waters. Tentative correlations have been made between cores based on curve trends.

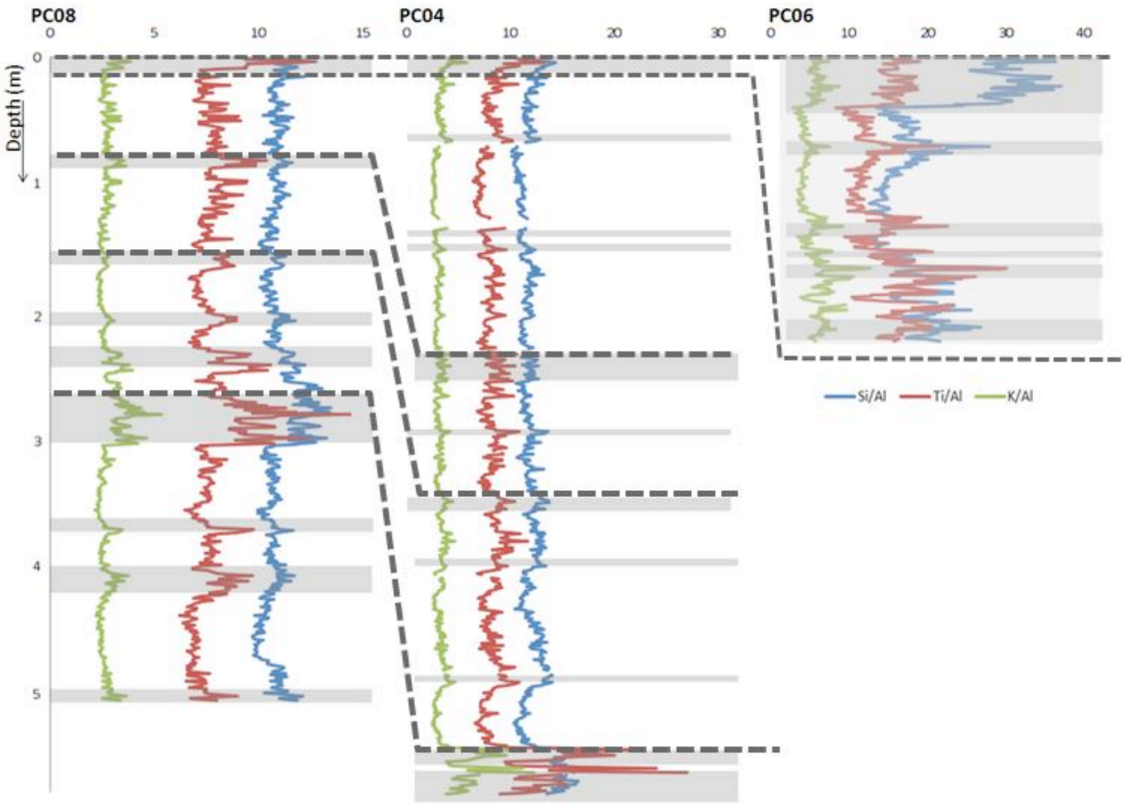


Figure 6.9: Tentative correlation using coincident Si/Al (blue), Ti/Al (red) and K/Al (green) peaks (shaded in grey).

6.3 Discussion

6.3.1 Modern Day Morphology of the Gulf of Cadiz

6.3.1.1 Eastern Gulf of Cadiz

The study reveals that the eastern Gulf of Cadiz contourite depositional system is highly complex and more varied than was previously thought. When combined with knowledge gathered from previous studies, the data collected here allows for a new detailed understanding of the morphology in the eastern Gulf of Cadiz (Fig. 6.10). Acoustic and core data has allowed for the identification of modern day morphological features and builds on work carried out by previous authors (Nelson et al. 1999; Habgood et al. 2003; Mulder et al. 2003; Hanquiez et al. 2010; Rogerson et al. 2012; Hernández-Molina et al. 2014). Core data has been used to identify changes in sediment provenance, facies and the resulting processes responsible for deposition. This has then allowed for a reconstruction of the MOW pathways prior to the Holocene global warming, and a new understanding of the changing influence of the MOW as driven by climatic changes is presented. The implications for morphological and oceanographic understanding are discussed herein.

The core sites show very different sedimentary and acoustic characteristics that are directly linked to their depositional environment and evolution over time. Figure 6.10 uses the bathymetric, acoustic and sediment data to create a present day morpho-sedimentary map of the study area. The upper and midslope features build on work published by Hernández-Molina et al. (2014). The map extends to water depths of approximately 1300 m, with the lower slope features being interpreted using observations from cores D13686, D13896, D13899 and D13900 (Table 3.2; Fig. 3.1), and published information (Habgood et al. 2003; Rogerson et al. 2005; Hernández-Molina et al. 2006; 2012; Zitellini et al. 2009; Hanquiez et al. 2010). Each key feature on the margin will be discussed herein starting from the shallowest water depths and working progressively basinwards.

The continental shelf is outside the scope of this study as the MOW does not affect the margin at these water depths (except for some periodic tidal movements close to the Gibraltar Gateway (Lobo et al. 2000). It is worth noting that Nelson et al. (1999) have completed a thorough study of the shelfal sediments. Key points to note from their study are: 1) The distribution of sedimentary features across the shelf is controlled by the SE flowing Atlantic Inflow Waters (consisting of the Atlantic Surface- and North Atlantic Central Waters); 2) Much of the shelf is dominated by a Holocene-aged mud, particularly offshore major river sources; and 3) Increased current velocities near the Gibraltar Gateway result in reduced mud deposition and the development of a sand dune field across the entire southernmost shelf (Nelson et al. 1993; 1999). The shelf is up to 40 km wide with the shelf break occurring at approximately 130 m. The Atlantic Inflow Waters (AI) sweep across the shelf in a southeasterly direction towards the Gibraltar Gateway (Baringer and Price 1999). A possible sediment source for the study area is sediment swept off the shelf by vigorous AI, and entrained into the MOW.

Core site PC06 is located at the shallowest water depths in the study area on the upper slope which has a slope gradient of 2-3° (Nelson et al. 1993). The upper slope is made up of actively-forming plastered contourite drifts that are influenced by the present day upper branch of the MOW (MU). Accumulation rates are high: ^{14}C dating puts the entire 2.4 m of core as Holocene in age. Two gently dipping (<1°) terraces, separated by a zone of steeper gradient steps, make up the mid slope section. Acoustic data shows that the terraces are highly erosive, with furrows, sand waves and sand ribbons. However, below this erosive surface, a thick (>800 m) contourite sand sheet is found (Antich et al. 2005; Stow et al. 2011). Sediment cores U1388 and BC05 are collected from within two contourite channels, one northern and one southern

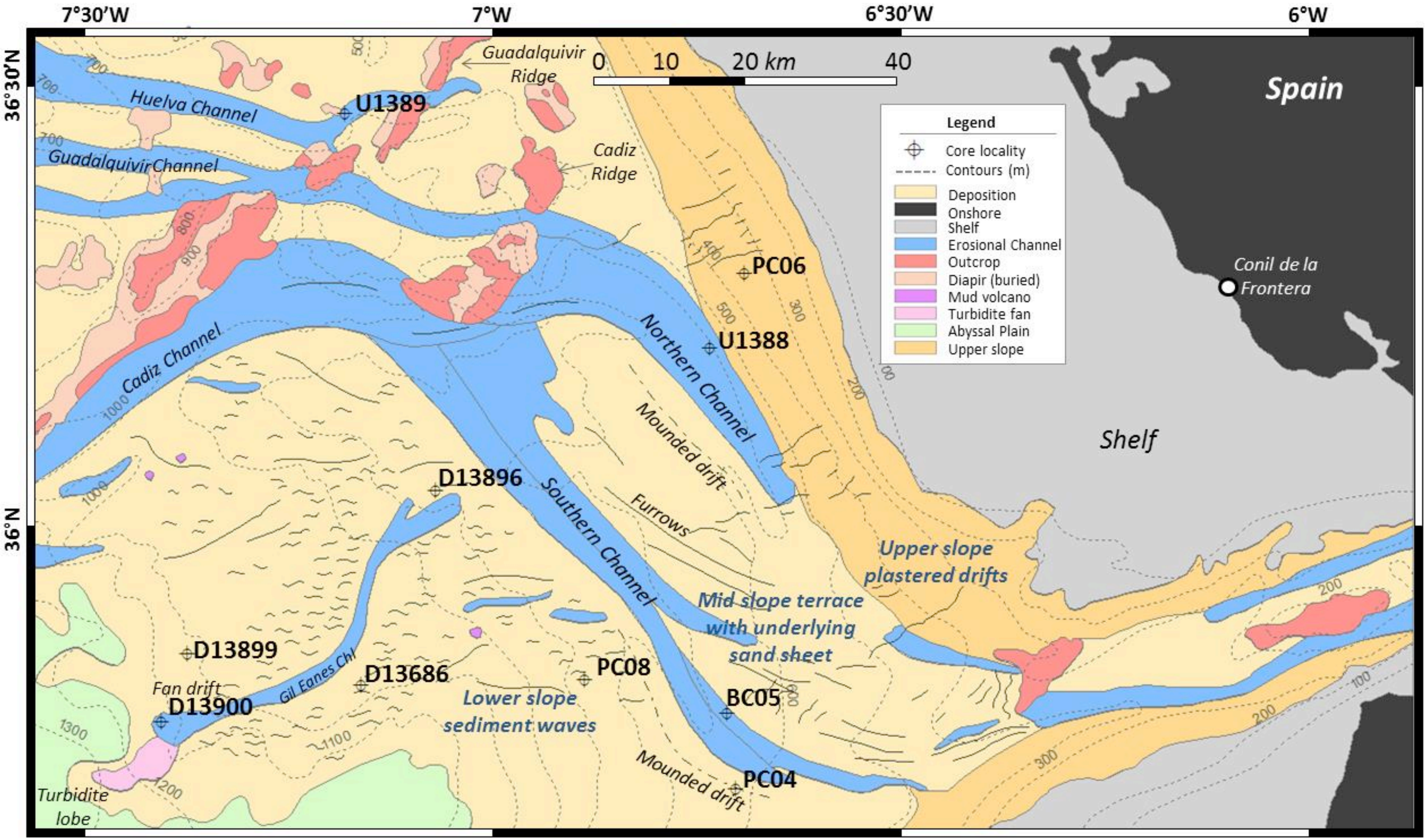


Figure 6.10: A morphological map of the eastern Gulf of Cadiz contourite depositional system. Modified from Nelson et al. (1993); Habgood et al. (2003); Mulder et al. (2003); Hanquiez et al. (2010); Hernández-Molina et al. (2014).

channel (Fig. 6.10), that incise the terrace in an alongslope orientation. These channels have similar morphologies, with erosion on the upper and deposition of mounded drifts on the lower channel flanks. Along the seaward boundary of the lower contourite terrace, a mounded contourite drift can be clearly imaged in seismic data. It reaches an elevation of approximately 100 m above the adjacent southern channel, diminishing in height towards the northwest (Hernández-Molina et al. 2014). Both PC04 and PC08 were collected from this drift which has a depositional crest orientated alongslope in a NNW-SSE direction (Fig. 6.10). The 'lee' side of the drift is covered in sediment waves that can be clearly imaged in the parasound data (Table 6.1).

There is evidence for contourite deposition across the lower slope. Named 'the overflow sedimentary lobe sector' by Hernández-Molina et al. (2006), Rogerson et al. (2005) name the lower slope broad sheet-like drift the Gil Eanes Drift. It is the downslope lateral continuation of the mounded drift located on the midslope (Fig. 6.10). A number of downslope- or oblique-orientated channels and furrows incise the lower and mid slope drifts (Hernández-Molina et al. 2014). The largest of these is the Gil Eanes Channel that descends from 900 m to 1200 m. It is 40 km in length, 1.5-3 km in width and orientated in a NE-SW direction (Fig. 6.10) (Habgood et al. 2003). At the termination of the channel is a contourite fan drift deposit from which core D13900 was collected. On the very lowermost slope, contourite deposition gives way to hemipelgic and localised tubidite deposition (Fig. 6.10) (Hanquiez et al. 2010).

6.3.1.2 The Algarve Margin

Previous studies have examined the present day northern margin of the Gulf of Cadiz in more detail than the data here allows. Sediment sampling in the region on the recent IODP 339 Expedition shows the large contourite drifts in the area (Fig. 6.11) are dominated by mud deposition and so is of little interest in this study. Despite this, there are large-scale erosional features in the area, and localised sand-rich sediment may be present within channels or moats.

The results across the entire region show a complex distribution of sand that is not solely related to a systematic deceleration of the MOW away from the Gibraltar Gateway (Fig. 5.1). Key observations are;

1) Close to the Gibraltar Gateway, erosion is prevalent. Non-deposition and erosion has led to large swaths of rocky outcrop on the sea floor in the most easternmost portion of the Gulf of Cadiz (Hernández-Molina et al. 2006; 2013).

2) There is a broad trend of decreasing grain size away from the Gibraltar Gateway towards the northwest and with increased water depth towards the west. There are however exceptions to this systematic decrease in mean grain size.
3) Contourite channels, as identified and mapped by Hernández-Molina et al. (2006) and Hanquiez et al. (2007), hold the highest sand portion. It is clear that morphological forcing or acceleration of the MOW plays an important part in controlling sand distribution.
4) There are high volumes of sand across drifts in the upper slope, and across the terrace and contourite channels of the mid slope of the proximal sector.

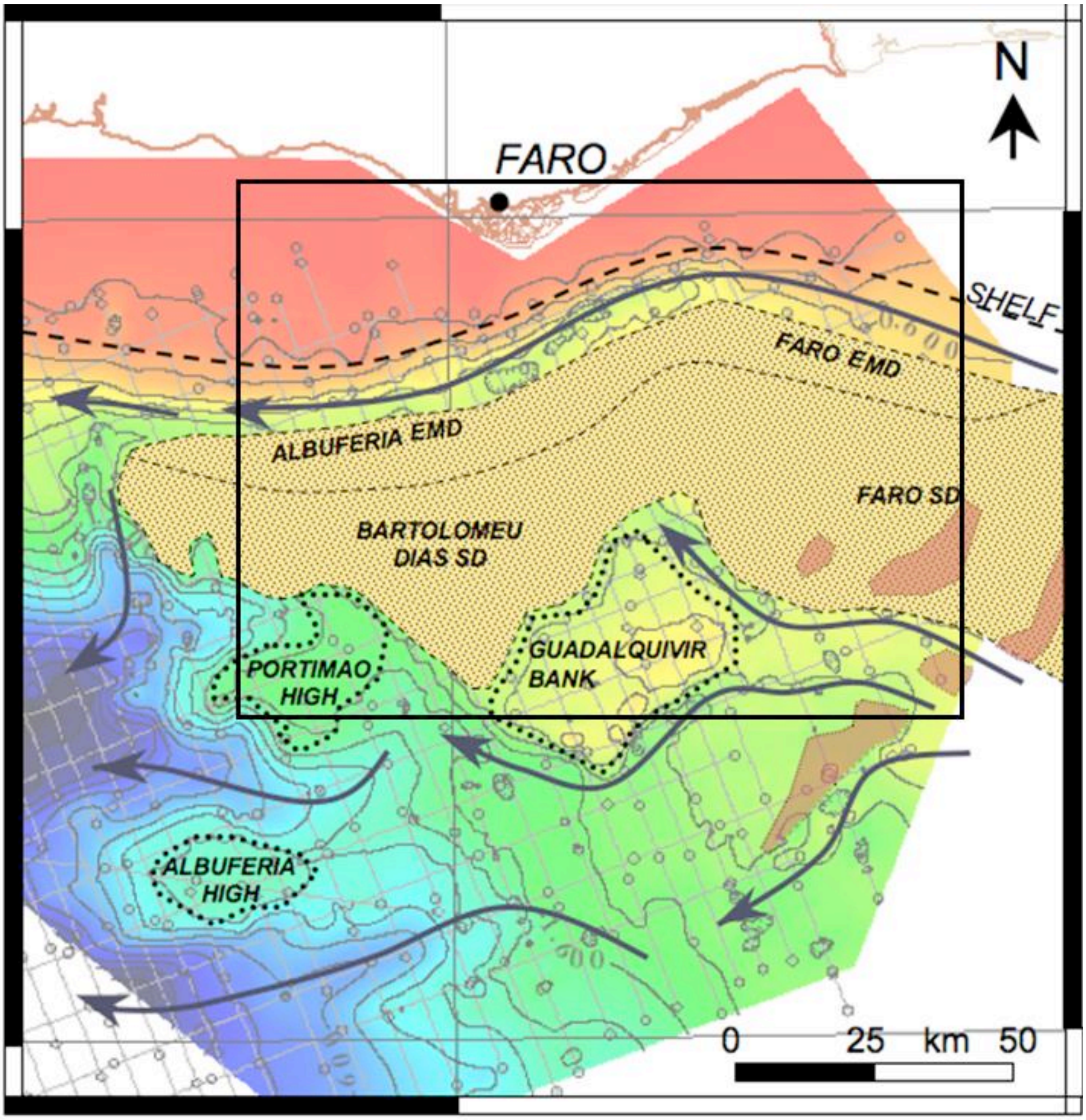


Figure 6.11: The present day morphological set up of the Algarve margin mapped over the depth to seabed. Based on seismic data from Llave et al. (2007a); Roque et al. (2102). Study area boxed. Bottom currents indicated by blue arrows. EMD = elongate Mounded Drift; SD = Sheeted Drift.

6.3.2 Margin Evolution and Palaeoceanographic Implications

6.3.2.1 Eastern Gulf of Cadiz

6.3.2.1.1 MOW flow paths over time

The modern day hydrodynamic set-up of the margin is well constrained thanks to extensive studies focused on of the nature of the MOW plume in the eastern Gulf of Cadiz (Fig. 6.12 A). The system is driven by the exchange of water masses at the Gibraltar Gateway, with the cold, relatively low salinity Atlantic Inflow Water (AI) exchanging with the dense MOW below. It is known that the AI is made up of the North Atlantic Surface- and the North Atlantic Central Waters that sweep the continental shelf and uppermost slope down to approximately 300 m accelerating and shoaling as it nears the Gibraltar Gateway (Nelson et al. 1999). Below 300 m water depth, the MOW is present in the form of a broad tabular flow with two main cores, the Mediterranean Upper Water (MU) and the Mediterranean Lower Water (ML) (Ambar and Howe 1979; Borenas et al. 2002; Hernández-Molina et al. 2011). Each core has different physical properties, with the Upper Core being warmer and less saline (13°C, 37.07‰) than the Lower Core (10.5°C, 37.42‰) (Zenk 1970; Baringer and Price 1999; Rogerson et al. 2012). These two cores are largely contained by contourite channel features in the eastern and central Gulf of Cadiz (Hernández-Molina et al. 2006; 2014). The route of the key water masses is thought to be typically representative of the pathways taken at previous interglacials throughout the Quaternary (Rogerson et al. 2005) (Fig. 6.12 A; 6.13 A).

The core data used in this study shows that contourite deposition has, in the past, been greatly reduced or even switched off across the upper slope evidenced by a change in facies from sand- to mud-dominated deposition below ~4.5 m in U1388 (Fig. 6.7). This is in agreement with observations from the central and northern Gulf of Cadiz where authors observe an enhancement of MOW intensity across the upper slope Holocene section marked by an increase of grain size (Stow et al. 1986; Nelson et al. 1993). Pre-Holocene, finer-grained sediments indicate that low energy conditions prevailed across the upper slope. This is coincident with an enhancement of bottom current activity across the mid-slope mounded drift, marked by an increase in grain size at core sites PC04 and PC08 below ~4.4 and ~5.25 m respectively (Fig. 6.7). This suggests a weakening of the MU during pre-Holocene glacial conditions, and an associated strengthening of the ML during glacials (Hernández-Molina et al. 2014). However, there is also evidence that the bottom currents affected the lower slope in the past. The lower slope core sites (D13075, D13899 and D13900) have mud-silt core tops, but all feature distinct sand layers at depth. A major sand body between ~2 and 4 metres in core D13900 (Fig. 6.7) has been dated by Rogerson et al. (2005) as representative of the last

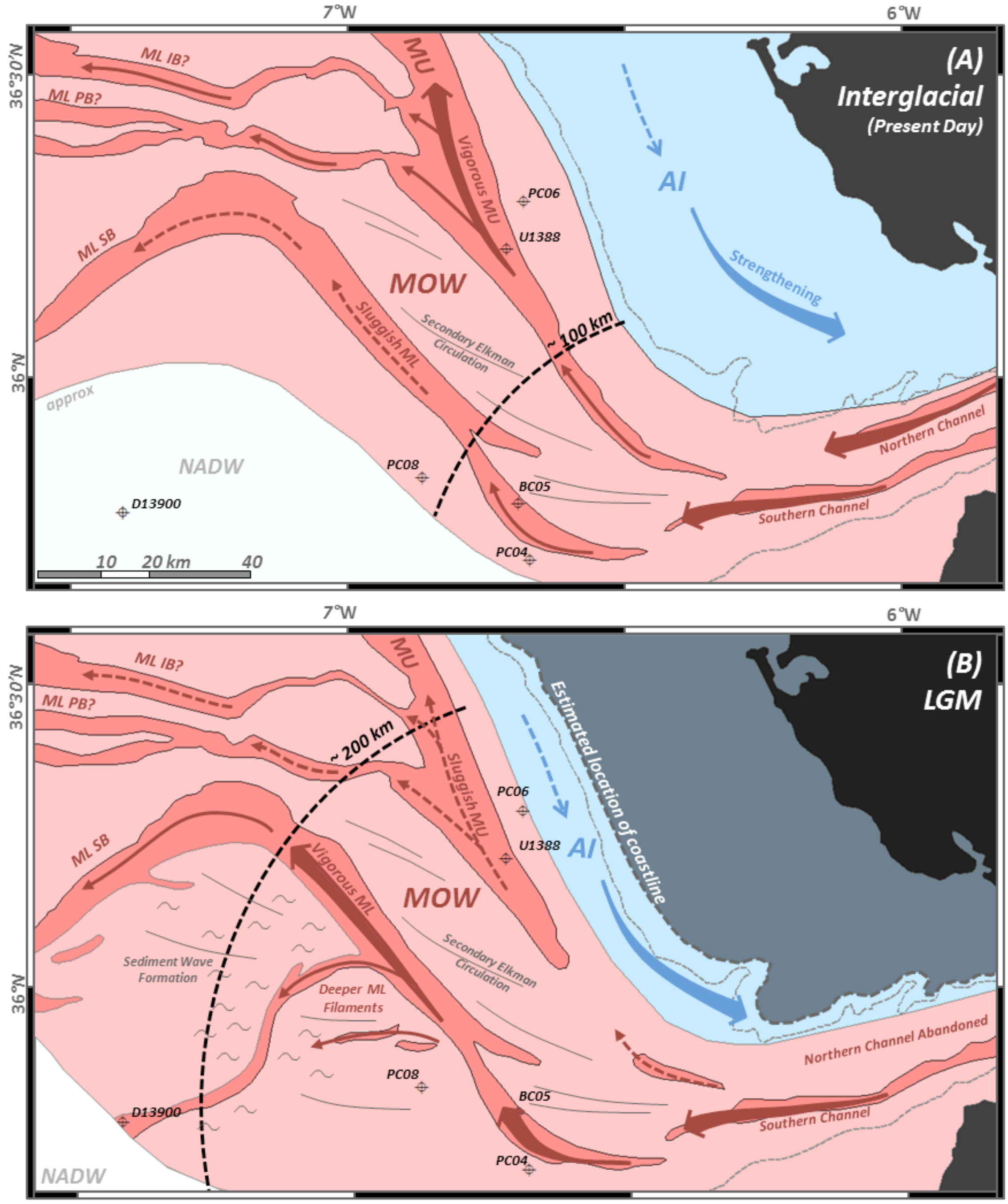


Figure 6.12: MOW flow in the eastern Gulf of Cadiz. A) During interglacial HST times (as present day). B) During glacial maxima (LST) times. The black line marks the approximate point where the water mass changes from a gravity-driven cascading water mass to a geostrophic one. AI = Atlantic Inflow Water; MOW = MOW; MU = Mediterranean Upper Water; ML IB = Mediterranean Lower Water Intermediate Branch; ML PB = Mediterranean Lower Water Principal Branch; ML SB = Mediterranean Lower Water Southern Branch (Llave et al. 2007b); NADW = North Atlantic Deep Water; LGM = Last Glacial Maximum.

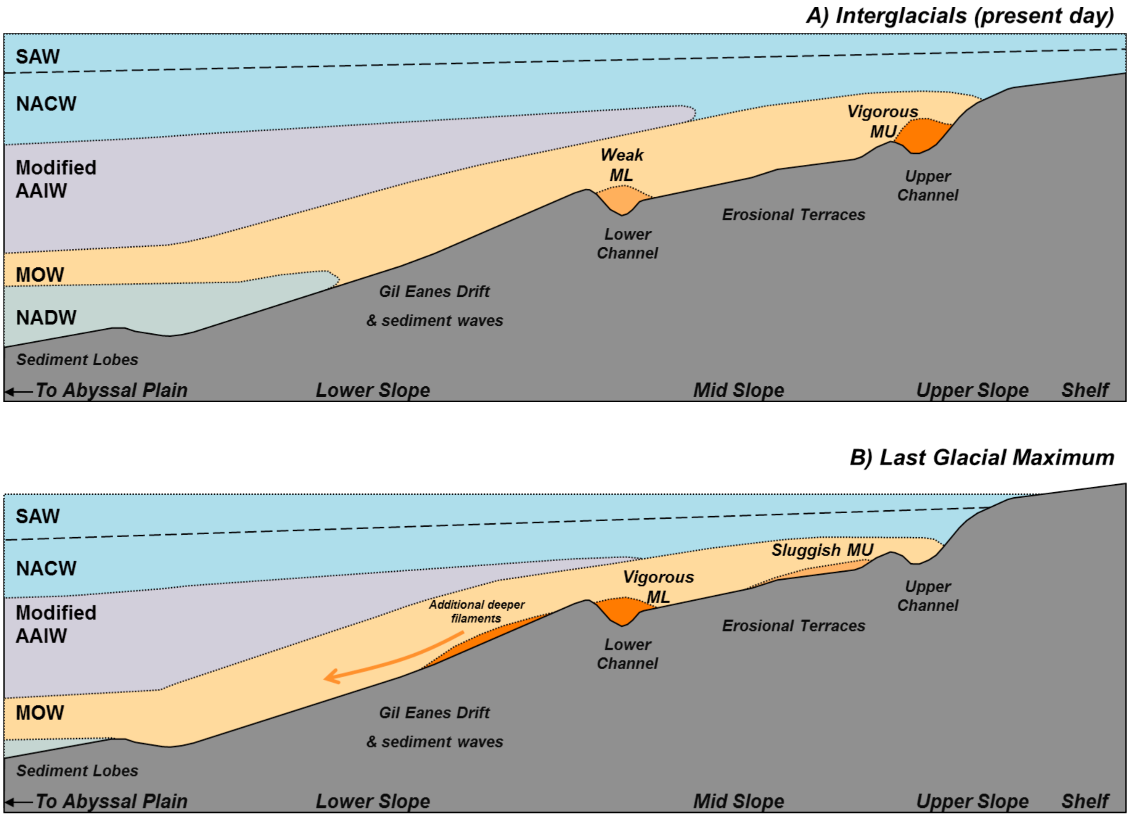


Fig. 6.13: Schematic (with exaggerated sea bed topography) of the changing settling depths of the main water masses in the study area relative to the observed morphology. SAW = Atlantic Surface Water; NACW = North Atlantic Central Water (which combine to form the Atlantic inflow Water); AAIW = Atlantic Intermediate Water; MOW = MOW; MU = Mediterranean Upper Core; ML = Mediterranean Lower Core; NADW = North Atlantic Deep Water. A) shows the present day oceanic set-up and represents those times in the past with interglacial climatic conditions. B) A schematic representation of a possible oceanic set-up during times of glaciation. During such climatic conditions, the MOW would have been denser and thus had a deeper settling depth. The upper channel shows little MOW activity during the last glacial maximum

glacial maximum. Other lower slope cores have sand bodies buried beneath muds at 2-5 metres that are dated Pleistocene in age (Habgood et al. 2003; Rogerson et al. 2005). These observations imply that pre-Holocene, the MOW affected the sea bed significantly *deeper* than the present day both with respect to relative sea level and its neutral buoyancy depth (Fig. 6.12 B; 6.13 B). The LGM saw sea-levels fall up to approximately 120 m (Fig. 6.12 B) and the water masses are expected to move with this fluctuation. However, increasing rates of deep water generation of increased density in the Mediterranean led to a deeper settling depth of the MOW being required before it reached its neutral buoyancy. The position of the MOW on the slope, controlled by the density gradient between the MOW and the Atlantic Waters, is further complicated by the presence of the two bottom water cores, the MU and ML. The location of these cores appears to be variable, moving up and down slope with the larger MOW water mass (Fig. 6.13). This is in agreement with oceanographic predictions by numerous authors working elsewhere in the Gulf of Cadiz who predict a deeper, more vigorous MOW during glacial conditions (Baringer and Price 1999; Schönfeld and Zahn 2000; Rogerson et al. 2005; Hernández-Molina et al. 2006; Voelker et al. 2006; Toucanne et al. 2007).

High cyclcity observed in the cores is attributed to the sensitivity of the MOW to global climatic fluctuations. In the broadest sense, there is evidence of shallow focused MOW during the Holocene, and a MOW that affects a deeper portion of the margin during glacials. Imprinted on this trend is evidence for high sensitivity to rapid climate fluctuations such as Heinrich events and Dansgaard-Oescher cycles which modify the position of the MOW cores on the slope and will alter the rate of bottom water influx into the Gulf of Cadiz (see next section). Rogerson et al. (2005) associate sandier facies on the lower slopes with increased glacial activity and calculate rapid shoaling of the MOW during times for deglaciation or Heinrich Events. Heinrich Events have been tentatively correlated across the cores (Fig. 6.7). All this evidence points towards a deeper MOW during times of glacial climatic conditions (lowstands) and a shallower MOW during interglacials (highstands).

6.3.2.1.2 MOW velocity over time

The velocity of the MOW and how it changes is difficult to dissociate from the movement of the water mass and the MU / ML cores. As a result, many authors have linked a weakening or strengthening of the MOW to climatic changes which in reality are a representation of MOW movement away from their study area.

Nevertheless, the *nature* (velocity, turbulence, core size) of the MOW is expected to have changed due to climatic oscillations. There are numerous factors that control a bottom current core velocity and size. Key controls identified are: 1) The rate of deep water production in the Mediterranean; and 2) The cross sectional area of the Gibraltar Gateway (Maldonado et al. 1999; Toucanne et al. 2007). Additional controls within the Gulf of Cadiz will be: 3) The morphology of the continental slope; 4) The extent of gravity-driven acceleration; and 5) The movement and density of other water masses in the Atlantic Ocean.

It is widely accepted that there was significantly enhanced bottom water generation in the Mediterranean during cold glacial periods on account of dry conditions and relatively cool surface water temperatures (Cacho et al. 2000; Voelker et al. 2006). This enhanced overturning would have provided denser Mediterranean deep waters during glacial times. The associated reduction in sea level during glacial periods will affect the cross-sectional area of the Gibraltar Gateway. With significant sea level fall and increased Mediterranean deep water density, the MOW would be expected to be diminished, but rapid climatic fluctuations appear to allow the MOW to remain established and it is further accelerated through the narrow Gibraltar Gateway, likely in part due to a thinning of the Atlantic Inflow Waters at the Gibraltar Gateway at such times (Rogerson et al. 2012). Erosional surfaces have been identified throughout the Quaternary deposits located in the central and western Gulf of Cadiz (Llave et al. 2006; 2007a). These have been linked to deglaciation events by Rogerson et al. (2012) or periods of rapid Atlantic Freshening. Sierro et al. (1999) have also linked discrete sand units in the upper slope with periods of rapid deglaciation. It is thought that sudden freshening of the Atlantic Ocean by ice melt increases the density gradient between the MOW and Atlantic Surface Waters, thus increasing the velocity and mixing (Rogerson et al. 2005).

The interaction of water masses on the sea bed in the eastern Gulf of Cadiz is further complicated by the gravity-driven overflow after the shallow Camarinal Sill in the Gibraltar Gateway down to the MOW settling depth. The MOW accelerates as it descends the sill, creating a highly erosive, turbulent water mass that mixes with the overlying Atlantic Inflow Waters (Legg et al. 2009). It is estimated that the majority of this mixing occurs within the first 50 km of the Gibraltar Gateway (Baringer and Price 1999) and the MOW reaches neutral buoyancy and becomes a true geostrophic current approximately 100 km from the Camarinal Sill (Fig. 6.12 A) (Legg et al. 2009). The subdivision of the MOW into the MU and ML is thought to be (at least in part) driven by differential mixing resulting in a warmer, less dense upper core and a higher salinity lower core. Of course, this lower core has a greater distance to decent into the Atlantic Basin before it become neutrally buoyant, and therefore it would be expected that it would be have a higher velocity. This is clearly seen in bottom current velocity data acquired over the last decades (Madelain 1970; Kenyon and Belderson 1973; Melières 1974; Zenk 1975; Baringer and Price 1997; Nelson et al. 1999) and compiled by Hernández-Molina et al. (2006) (Fig. 6.14). The modern day set-up is fairly well constrained (Fig 6.12 A). However, the expected deepening of the MOW during glacial times will affect the cascade. During glacial times, when the MOW is predicted to have a much deeper neutral buoyancy depth, the overflow cascade would have been extended away from the Gibraltar Gateway. Evidence from the lower slope cores shows that vigorous bottom currents were capable of depositing sands at 1300 m water depth. The sands of D13900 are deposited in a fan drift at the termination off a principally downslope-orientated channel. This suggests a gravity-driven, cascading ML being in action 150-200 km away from the Gibraltar Gateway during glacial times (Fig 6.12 B). Incidentally, it is worth noting that the estimated modern day limit of the MOW cascade (100 km approximately according to Legg et al. (2009)) is roughly where the mounded drifts form, both the upper minor mounded drift on the upper terrace, and the large midslope mounded drift from which PC04 and PC08 were collected (Fig 6.12 A). This cascade deepening may explain some of the unusual morphological features observed across the eastern Gulf of Cadiz. The southern channel and Gil Eanes mounded drift are much larger than the upper channel and drift. This may be explained by its interaction with a more vigorous water mass that is accelerating due to gravity as it cascades over the Camarinal Sill.

Finally, the morphology of the Gulf of Cadiz will have a clear role in locally enhancing the MOW due to morphological forcing. Today, the MU and ML are largely contained within two alongslope orientated channels that concentrate and further accelerate the bottom current cores. This leads to intense erosion along the channels and across the contourite terrace. This is very different to the morphology on the lowerslope where sand waves and downslope orientated 'blind channels' predominate. This is indicative of a broader MOW that must have flowed across large swaths of the lower slope, and was locally enhanced in narrow channels. The largest feature is the southern channel and associated mounded drift. This is interpreted to be due a deeper broad MOW during interglacial, and a vigorous ML core within the adjacent southern channel (Fig. 6.12; 6.13).

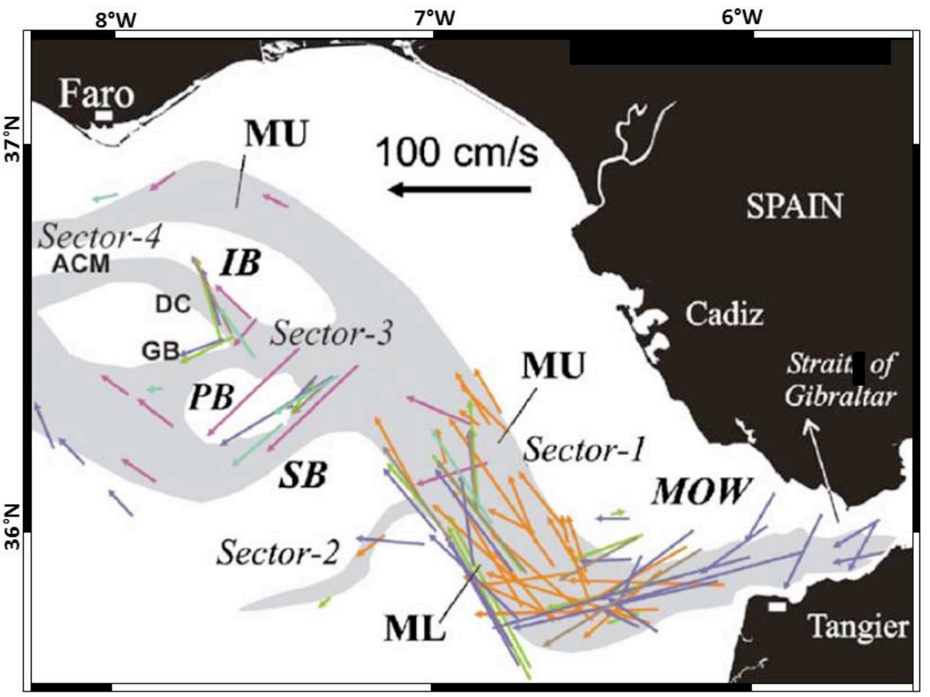


Figure 6.14: Compilation of modern current water velocity data taken from Hernández-Molina et al. (2006). Figure uses data from Madelain (1970); Kenyon and Belderson (1973); Melières (1974); Zenk (1975); Baringer and Price (1997); Nelson et al. (1999). Data shows that high bottom current velocities are observed close to the Gibraltar Gateway (> 100 cm s^{-1}). Highest velocities are observed along the ML core due to gravity-driven acceleration.

6.3.2.2 The Algarve margin

Along the Algarve margin, the evolution of the system can be examined on a much larger scale. This mixed downslope-alongslope system and its acoustic response can tell us a great deal about the oceanographic evolution of the Algarve Margin from the Miocene to present day. The Pliocene section demonstrates a battle for dominance between multiple depositional processes. Analysis of the seismic data reveals some idea of the palaeoceanographic set-up of the margin. A number of authors have studied this area, and a multitude of difference interpretations have been provided (Fig. 3.4). This study is largely in agreement with the dating of the units from the most recent studies (Llave et al. 2011; Roque et al. 2012) but also identifies a previously overlooked, highly eroded unit, named here PQ. Evidence gathered from the eastern Gulf of Cadiz shows that there is a basinwards shift of the dominant MOW core during times of lowstand (see Section 8.1). This is in agreement with additional studies across the wider Gulf of Cadiz margin (Nelson et al. 1993; Stow et al. 2002b ; Llave et al. 2006) and the work presented on the eastern Gulf of Cadiz here. Therefore, since the Algarve margin is influenced by the upper core of the MOW, it would be expected that the most vigorous bottom currents are associated with highstand interglacial conditions. However, problems arise with tying large-scale seismic units to global eustatic sea-level curve (Miller et al. 2005) (Fig. 6.15). Neotectonics, local relative sea-level changes, bottom current production rates and the exchange of water masses at the Gibraltar Gateway will further complicate the control of eustacy on the system. Figure 6.15 summarises the relationship between sea-level and the drift evolution and will be discussed, with additional controls below.

Along the Algarve Margin contourite succession, high cyclicity is observed in the acoustic data, indicating that there have been times of increased velocity and times of waning bottom currents. Sea level fluctuations during the Pliocene and Quaternary are varied. Broad trends seen include a reduction in sea level during the Quaternary and a move to more extreme sea level fluctuations as a result of the change to dominance of the 100 ka Milankovitch cycles. Here we examine the paleaoceanographic implications of the Pliocene sequence.

Discontinuity M separates the Miocene from the lower Pliocene and signifies the opening of the Gibraltar Gateway after the Messinian Salinity Crisis at approximately 5.3 Ma (Roveri et al. 2014). Subsequent discontinuities represent times when bottom current velocities were enhanced sufficiently to cause widespread or localised erosion of the sea floor. However, it took some time for the MOW to become fully initiated, and it is though that a downslope system remained dominant throughout the Messinian into the earliest Pliocene (P1 section (Fig. 6.2; 6.16). Seismic unit P2 represents the full onset of the MOW and the resulting discontinuity, the LPR, has been dated at approximately 4.0-4.2 Ma (Llave et al. 2011). This occurred at a time of low then rising global eustatic sea level (Miller et al. 2005). The high amplitude acoustic response of the contourite section of seismic unit P2 topped by an erosive discontinuity indicates accelerating bottom current velocities at this time and the deposition of a sandy sheeted drift (Fig. 6.2; 6.16). Global sea level trends (Fig. 6.15) show a relative high at this time (Miller et al. 2005). In addition, there is a strong influx of debrite deposits to the system. Downslope processes are most commonly associated with sea level lowstand (Catuneanu 2006), indicating that there may have been some additional control on the system at this time, for example a major tectonic event, or destabilisation of the margin by the introduced bottom current. Seismic unit P3 has been interpreted as a time when relatively weak bottom currents were in action over the drift. During this time, there was a dramatic fall in sea-level followed MOW was significantly increased (Khelifi et al. 2009) and it is likely that the semi-transparent seismic unit P3 is representing a weaker Upper Core of the MOW, while

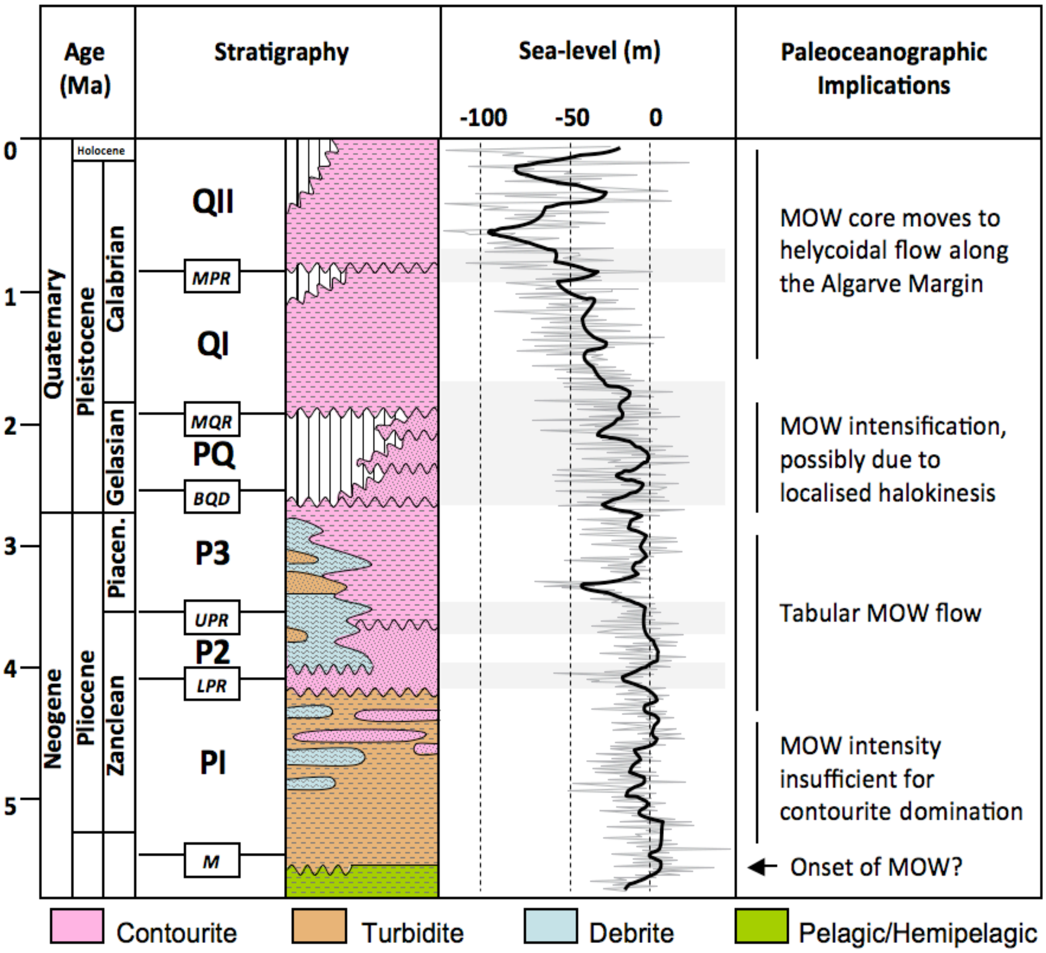


Figure 6.15: The palaeoceanographic implications of each depositional sequence. Grey shaded areas indicate major erosive events. Although some potential ties are seen between times of enhances bottom water currents and eustatic sea-level lowstand, there must addition allogenic controls on the system. These are ties to alternative forcing such as tectonics and halokinesis. Eustasy curve from Miller et al. (2005).

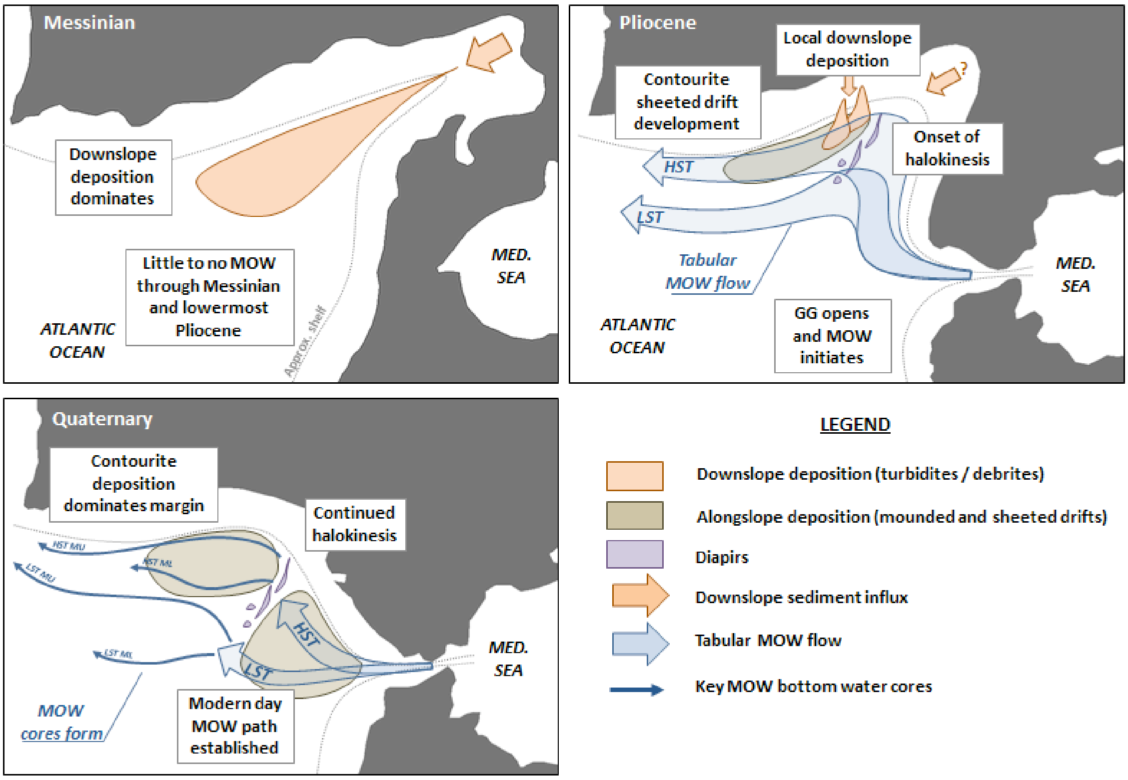


Figure 6.16: Schematic representation of the long-term evolution of the Gulf of Cadiz. Coastline from Garcia Mojonero et al. (2011).

the Lower Core was intensified elsewhere along the margin at greater depths (out of the study area). Seismic unit by a relative highstand (Fig. 6.14), although fluctuations in eustasy continued throughout the latest Pliocene. Proxy data shows that in the Late Pliocene (3.5-3.3 Ma) the density of the PQ returns to high amplitude reflections with multiple erosional discontinuities. The section is completely absent along much of the upper slope due to erosion. This indicates a time of enhanced MOW circulation in the upper core. The global sea-level curve shows repeated high amplitude fluctuations at this time. In addition, the seismic indicates that this was a time of accelerated diapir growth to the east of the study area, and the associated move from tabular water masses (likely to form sheeted drifts) to the distinct bottom water cores of the MU and ML (more likely to erode channels and form mounded drifts). Therefore the exceptionally vigorous bottom currents can be attributed to high amplitude eustatic fluctuations enhanced by neotectonics (Fig. 6.15).

Three important conclusions from detailed palaeoceanographic studies can be made based on this work: 1) There does appear to be some link between eustasy and bottom current velocity, which in turn will affect the evolution of the margin on a seismic scale. However, caution must be executed to consider additional controls such as tectonics; 2) In this region, it appears that the relationship between climatic and eustatic fluctuations is complicated by the nature, magnitude and amplitude of the change; and 3) Finally, the water mass itself has an important influence on the type of system that will develop. Processes that trigger turbulence or core formation in a tabular bottom current mass can significantly alter the development of a contourite depositional system, such as the move from sheeted to mounded drift observed here. The above observations show that seismic facies, acoustic amplitudes and seismic stratigraphic techniques can be used to analyse palaeoceanography on an alongslope and downslope mixed system, although all must be used to come to a robust conclusion.

The work carried out here will also be used to characterise contourite sands and mixed systems on seismic (low resolution where few depositional features are clearly imaged), as well as assess the controls on these systems in the next chapters.

6.3.3 Sediment Provenance

6.3.3.1 Eastern Gulf of Cadiz

There is compositional evidence for changing provenance over time across the Quaternary eastern Gulf of Cadiz section. Figure 5.13 shows the clustering of compositional data across two main trends. A detailed study of provenance has not been completed here, however some tentative interpretations have been made. These are attributed to alongslope transport vs. downslope sediment influx.

One of the principal sediment sources for the Gulf of Cadiz contourite depositional system is thought to be supplied by the Atlantic Inflow Waters (AI). Nelson et al. (1999) note that the AI, which flows southeastwards over the continental shelf, accelerates as it approaches the Gibraltar Gateway, as evidenced in the formation of a large sand dune field at the south eastern end of the shelf (Lobo et al. 2000). These accelerated waters will cause the suspension and transportation of sediment that may subsequently become entrained in the vigorous MOW that reaches velocities of up to 100 cm s^{-1} most proximally to the Gibraltar Gateway (Serra et al. 2010).

There is additional evidence for periodic downslope transportation from the shelf evidenced in small-scale downslope orientated slope gullies and slumps along the upper continental slope (Nelson et al. 1999). These may act as more direct sediment transport pathways connecting the shelf with the upper and midslope contourite features. Two distinct compositional trends are identified at core site PC06 (Fig. 6.6 C). They indicate that at times sand-rich sediment is largely derived locally from the shelf (PC06 Unit 1), and at other times an alongslope source was more dominant (Units 2-3) . The mechanisms for shelf spillover processes remain poorly understood, but internal waves at the interface between the MOW and Atlantic Inflow Waters (AI) may play an important role. On a larger scale, the downslope-orientated gullies on the upperslope are likely important sediment conduits to the system. They roughly correlate to the predicted lowstand interface between the MOW and AI. This suggests that shelf spillover and alongslope reworking plays an important role during highstand, however downslope sediment influx is more important during lowstand. Although no compositional data was acquired for core site U1388, it may explain the dramatic change of facies observed between the Holocene and Pleistocene successions (Fig. 6.7). Such mechanisms may explain the relatively sandy depositional features identified across the upper and midslope compared to the increasingly mud-dominated sedimentation on the lowerslope.

Contrary to the expected sequence stratigraphic response of high downslope influx during lowstand (glacial conditions) (Catuneanu 2006), there are suggestions in the literature that the opposite may be seen in the Gulf of Cadiz. Toucanne et al. (2007) suggest that a warm, wet climate on the Iberian Peninsula during interglacial events may lead to increased sediment influx to the upper slope due to increased fluvial outwash (Thomdycraft and Benito 2006). This could be an additional provenance for the upper slope sediments and explain the composition differences seen between units at core site PC06 (Fig. 6.6 C).

Compositional data from midslope piston cores PC04 and PC08 shows both these core sites consist of sediments of the same provenance. It is likely made up of a mix of sediment derived from the Gibraltar Gateway (by erosive processes), biogenic material settling through the water column, and sediment entrained from the Spanish and Moroccan continental margins. Fe-stained Quartz in some beds suggests a possible wind-blown provenance element also. This is an area for further work.

6.3.3.2 Algarve Margin

The study of the Algarve Margin, based solely on 2D seismic data, is of a much larger scale, and little can conclusively be said about the sediment provenance. However, even on this large scale, some important points can be discussed on the interactions between downslope and alongslope processes.

There is clear evidence for downslope sediment influx to the basin throughout the Pliocene. Seismic Unit P1 has been interpreted as distal confined turbidite system (Fig. 6.2 P1). The initiation of the MOW is poorly constrained, and it is thought that it had little influence over the region in the earliest Pliocene when it formed a very sluggish flow. If the MOW velocity had been sufficiently vigorous, local reworking of downslope sediments may have occurred. This is the case in Seismic Unit P2, where more vigorous MOW waters appear to interact with mass wasting deposits in the northeast of the study area (Fig. 6.2 P2). This downslope system would have played a key role in providing sediment to the adjacent contourite sheeted drift through pirating and winnowing processes. Such deposits hold important economic potential on account of their possible sandy nature, and likely provides the most sand-rich deposits across this northern margin.

6.4 Conclusions

Two sandy contourite systems of different ages have been examined in this study and their evolution reconstructed at different scales. The Late-Pleistocene and Holocene of the eastern Gulf of Cadiz sandy contourite depositional system has been reconstructed using soft sediment cores with acoustic data. This is in contrast to a buried Pliocene sheeted drift and mixed system for which seismic data was used to identify changing depositional processes over the last *ca.* 5 Ma.

Although the two systems examined here have been described at different scales, some important comparisons and contrasts can be identified. The recent eastern Gulf of Cadiz can be named a sand-rich contourite depositional system – where alongslope processes dominate the margin and shape the seabed morphology. The Algarve Pliocene section is thought to also show sand-rich contourite deposits, particularly in seismic unit P2, but the strong control and interaction of downslope sediments mean that this system is classed as a mixed system with an associated sheeted drift.

The observations in the *Eastern Gulf of Cadiz* allow us to construct two regional maps of MOW flow; one for interglacial (present day) conditions (Fig. 6.12 A) and one for times of glacial maxima (Fig 6.12 B. It should be noted, the evidence presented here represents the last glacial cycle, and the data does not extend to the last interglacial. Seismic evidence from the eastern and northern Gulf of Cadiz shows that high cyclicity has been the norm throughout the Quaternary. Previous studies have identified the weak initiation of the MOW sometime in the early Pliocene. A significant increase in coarser (sand-sized) sediment noted in the eastern Gulf of Cadiz between the Pliocene and Quaternary succession (Hernández-Molina et al. 2014) represents a sudden enhancement of MOW flow which was sustained throughout the Quaternary. The Mid Pleistocene Transition marks the move from 40 ka climatic cycles to higher amplitude 100 ka cycles, and this is thought to have further intensified the contourite deposition and cyclicity of the Gulf of Cadiz sediments. It is therefore likely that the magnitude of MOW settling depth differences between glacial and interglacial cycles observed in this study have been in action since the Mid Pleistocene Transition 900 ka BP.

Studies in the western and central Gulf of Cadiz show that cyclicity in the Quaternary can be linked to climatic changes (Llave et al. 2006; 2007c), as is seen in the eastern Gulf of Cadiz. This study is the first in the eastern gulf of Cadiz to use evidence gathered from the entire continental slope (upper and lower) to make conclusions of the evolution of the MOW over time using sedimentological and remote sensing techniques. All this evidence from the study data and literature allow for the following interpretations to be made;

1) The MOW influences the mid- and lower-slope during glacial conditions and the upper- and midslope during interglacials (as is seen today) (Fig. 6.12; 6.13).
2) Rapid climate changes (deglaciations leading to Atlantic freshening) appear to be linked to times of enhanced erosion across the entire margin (Rogerson et al. 2005).
3) The MOW is much more mobile and variable than previously thought as a result of its sensitivity to climatic fluctuations and eustatic fluctuations.

Along the *Algarve Margin*, in the northern Gulf of Cadiz, a buried mixed alongslope-downslope system has been identified in the Pliocene succession. Analysis of seismic data shows the gradual move from a turbidite-dominated towards a contourite-dominated margin, and the subsequent 'birth' of an impressive elongate mounded contourite drift system; the Faro-Albufeira drifts. A Pliocene contourite drift was distinguished from turbidite deposits based on the acoustic character, distribution analysis and through careful margin reconstruction. In the earliest Pliocene, seismic unit P1 has been interpreted as a downslope-dominated (most likely turbidite) system sourced mainly from the northeast. There is clear evidence of alongslope-downslope interaction in seismic unit P2, where upslope progradation and a sheeted morphology are observed. Nevertheless, in the northeast of the study area, a thick sequence of chaotic seismic facies has been interpreted as debrites sourced from the north. Evidence for more vigorous activation of the MOW in sequence P2 is seen basinwards in the form of extremely high amplitude reflections. However, the bottom currents were unable to dominate over the entire margin due to high down-slope clastic influx. Semi-transparent seismic unit P3 indicates that the upper Pliocene initially experienced a reduction in bottom current intensity, however upslope progradation shows that a mixed system was maintained. Above the Base Quaternary Discontinuity, highly erosive surfaces and high amplitude seismic reflections are evidence of pronounced intensification of the MOW and a move to a fully contourite-dominated slope.

Both the studies have been carried out on different scales to demonstrate the complexity of controls on the system over time. On a seismic scale, the evolution of the contourite systems is controlled by important oceanic events, tectonics and downslope sediment influx. On a sediment scale, climatic fluctuations and sea-level changes are the key control.

Interpretation & Discussion

7 Characterising Contourite Sands

The Gulf of Cadiz provides the perfect natural laboratory for the study of contourite sand systems. Despite the data being acquired from this one system, the observations recorded here are also repeated in many other contourite depositional systems across the oceans. Here the results of the previous chapters are compiled and discussed with the aim of aiding contourite sand identification in the future. Using the bathymetric data, seismic data and sedimentological analysis, the morphology of the Gulf of Cadiz has been mapped out and different sand-prone depositional environments identified (chapter 6): 1) Contourite channels; 2) Erosional terrace deposits; 3) Sandy sheeted drifts; and 4) Sand units within plastered, fan and mounded drifts. The large-scale features observed in seismic are outlined, with a focus on the identification of sandy sheeted drifts as seen in the Pliocene of the Algarve margin. Facies and facies sequences identified in chapter 5 are discussed, and a move towards a new model for contourite facies is proposed. The textural results from chapter 5 will be used to identify any characteristic trends within the textural data that may aid to differentiate contourite sands from other deep water facies. This builds on previous work focusing specifically on contourite sands (Lovell and Stow 1981; Viana et al. 1998; Viana and Rebesco 2007). Some deep water sands interpreted elsewhere as contouritic show different features to those observed here (Shanmugam et al. 1995; Shanmugam 2003; Martín-Chivelet et al. 2008; Mutti and Carminatti 2012). These discrepancies within the literature on the diagnostic features of contourite sands will be addressed here, and developed further in chapter 9.

7.1 Key Features at Seismic Scale

The seismic characteristics of the sandy contourite depositional system in the east and the buried sheeted drift found in the Lower Pliocene succession in the north of the Gulf of Cadiz are examined in detail with a particular focus on sandy sheeted drifts. The close relationship between downslope and alongslope processes is also discussed. This will be carried out at the scale of the drift to that of the seismofacies.

7.1.1 Drift-Scale Characteristics

Since contourite drift types are named on account of their external morphology (McCave and Tucholke 1986; Faugères et al. 1999; Rebesco and Stow 2001; Stow et al. 2002c; Faugères and Mulder 2011), the drift identified in the Pliocene offshore the Algarve margin can be classified as a sheeted drift *with* a mixed system. The overall morphology is that of consistent thickness and is mapped extending over 2000 km^2. Thinning occurs only close to the basin margins (along the upper slope and Guadalquivir Bank and against some (but not all) diapirs in the east of the study area). Since its deposition, the drift has been deformed by ongoing halokinesis and faulting along the margin, but the original broad, low-mounded morphology is still evident through careful margin reconstruction (seismic flattening) and is strikingly different to the overlying mounded elongated and separated Faro-Albufeira drifts.

Sand-rich drifts are generally sheeted in morthology and show an overall elongated distribution. The same can be said for contourite channels in which contourite sands can accumulate. This highlights an important consideration when identifying sheeted drifts in the sub-surface; prior knowledge of the oceanographic set-up of a margin can aid contourite recognition. Along the Algarve Margin, the Pliocene oceanographic set-up is moderately well constrained (Hernández-Molina et al. 2011). It is well known that the opening of the Gibraltar Gateway occurred around the Miocene-Pliocene boundary. Estimates for the full onset of the MOW are around the time of the Lower Pliocene Discontinuity (LPR). This provides good evidence for oceanographic conditions favourable to drift formation. Elongation of a sediment body alongslope can, when combined with knowledge of the palaeoceanographic set-up, aid the recognition of contourite drifts, specifically sandy sheeted drifts, in the subsurface.

7.1.2 Discontinuities and Seismic Unit Identification

Regionally extensive erosional discontinuities are often important criteria for contourite identification at seismic scale, an example of which is actively forming on the sea bed over the erosional terrace in the eastern Gulf of Cadiz. Previous work in the northern Gulf of Cadiz (Llave et al. 2011; Roque et al. 2012) has identified key discontinuities based on laterally continuous high amplitude reflections, and reflection teminations. However, discontinuities in the study area are not always clearly erosive at a seismic scale, but can be due simply to a reorganisation of the hydrodynamic set-up of the margin (for example the movement of the bottom water core over, or away from the region). In such cases they can be identified by a distinct regional change in the acoustic response of the package. Where the nature of the discontinuity is erosional, the acoustic impedance between the under- and over-lying seismic packages may not necessarily be significant. The nature of high-energy contourite deposition is one of gradual waxing and waning flow. Erosional discontinuities correlate to times of enhanced bottom current velocity, such as is seen in the uppermost Pliocene to Lowermost Quaternary along the Algarve Margin. During such times the current has erosional capabilities. The gradual waning of flow results in deposition of sediment particles from the moment that the transport capacity drops below the erosional threshold. Therefore there is not necessarily a hiatus in the sediment record where digenesis, or hard ground formation may form a remarkable seismic reflection, but the acoustic impedance depends solely on the different acoustic response of the over- and underlying sediment packages. As a result, many of the discontinuities identified are highly variable in amplitude and can demonstrate low acoustic impedance between under- and over-lying seismic packages (low-amplitude reflections). Consequently, discontinuities in contourites should be identified through the observation of truncation, onlap and downlap of the seismic reflections and not solely using the identification of laterally continuous high amplitude reflections. Care must be taken to accurately distinguish between depositional onlapping patterns and those relating to infilling due to tectonic movements. Flattening can aid the identification of convex-upwards onlap patterns (likely depositional onlap) versus concave-upwards onlap patterns (likely tectonic-related infilling of sediments). These features can be very subtle and clues to the origin of a discontinuity can also be gathered by observing thinning vs. thickening against lines of movement (faults / diapirs) in relation to changing sediment accommodation space.

7.1.3 Depositional Unit-Scale Characteristic

Typical characteristics of sheeted drifts on the sea floor have been outlined in the literature. Faugères et al. (1999) note that sheeted drifts, both accumulating on the abyssal plain and plastered along continental slopes (as in the case of the eastern Gulf of Cadiz) show little to no progradation of seismic units. They observe that “gently downlapping reflections show only slight down-current progradation with either a basinward or landward oblique component”. In the buried Pliocene sheeted drift along the Algarve Margin this is certainly the case. Sequences identified across the drift are aggradational in nature. There is some evidence of minor progradation, including upslope which is often an indication of contourite influenced sedimentation (Fig. 6.3). The intense interaction with downslope processes to the east of this system (Fig. 6.2 P2; P3) may disguise further prograding packages. Individual units are seen to downlap with a concave-upwards trend and are interpreted as prograding alongslope to the west. Sequences also thin towards many of the diapirs in the east of the study area, indicating active halokinesis at the time of deposition. Additional features observed at this scale that give clues to the sandy nature of the contourite deposit are channels that also tend to be orientated alongslope or obliquely. These are imaged as erosional features causing reflection truncation that is usually amplified on one margin. As a result, channels are often asymmetric and may show an associated depositional feature (drift) on one channel margin, usually the downslope margin. They are also often associated with broad seaward-dipping erosional terraces that form non-deposition surfaces and cause wide-spread erosional surfaces. Channel fill is usually high-ampitude and chaotic in acoustic signature and thought to be sand and gravel rich (see next section).

7.1.4 Seismofacies-Scale Characteristics

Seismofacies are extremely variable in any sediment body and cannot solely be used to determine contouritic origin of a deposit. In the case of the Upper Pliocene drift of the Algarve Margin however, seismofacies do give a strong indication of the presence of a contourite sheeted drift as it can clearly be distinguished from other deposits based on the acoustic response. High amplitude and laterally continuous reflections can be identified and are in contrast to the chaotic downslope sequence seen close to the continental slope (Fig. 6.3). These seismic facies are seen to be interbedded in the overlying units where contourite sediments begin to dominate over downslope processes. Locally, where the turbidite lobes and contourite sheeted drifts are stacked, both sequences show very similar acoustic characteristics, and so they have been interpreted based on other observations on a larger scale.

In the eastern Gulf of Cadiz, where the seismic resolution is greater, a number of seismic facies are observed (Table 6.1) representing depositional vs. erosional processes. Sediment waves are imaged both actively forming on the sea bed and in the subsurface. These can be used as a useful diagnostic tool for contourite sedimentation where orientated alongslope (or oblique to slope) and have also been identified in the subsurface along the Brazilian continental margin as both transverse and barchan in shape (Viana et al. 2007). They show gentle prograding seismic reflections and regular minor erosional surfaces. Waves may be sand or mud-dominated. Modern channels show a characteristic hyperbolic response in parasound data and a rough, bright sea bed reflector in seismic. Channel fills are generally chaotic and low amplitude. Other erosional feature to note in contourite systems are erosional terraces and furrows. Furrows form small indentations in seismic reflections and where they are seen at mappable resolution will tend to be orientated oblique to slope. This is on account of secondary (Elkman) circulation at the base of the bottom current mass. They can reach tens of kilometres in length and have been identified in contourite depositional systems worldwide (Viana et al. 2007).

7.1.5 Discussion

The recognition of contourite drifts on seismic can been a problematic, particularly where turbiditic processes are also ongoing since the seismic response is often similar. Three key criteria for identification have been proposed: 1) The presence of major discontinuities across the entire drift region that represent erosional or hiatus surfaces formed by major hydrological events; 2) The presence of depositional units exhibiting convex-upwards geometry; and 3) Progradational and aggradational stacking patterns (Faugères et al. 1999; 2011; Rebesco and Camerlenghi 2008). Using these criteria, many mounded drifts have been identified both on the modern sea floor (Faugères et al. 1993) and in the subsurface (Hüneke and Stow 2008).

Identification of sheeted drifts and other sand-prone contourite accumulations has proven more problematic, particularly in the subsurface. Limited examples do exist, for example, in the Campos Basin (Moraes et al. 2007), Danish Basin (Surlyk and Lykke-Andersen 2007), the North Rockall Trough (Stoker et al. 1998), Argentine slope (Hernández-Molina et al. 2009) and the Antarctic Margins (Maldonado et al. 2003). Some of them have been recognised, as with the Algarve Margin buried sheeted drift, due to their close relationship with turbidite and mounded contourite deposits respectively.

Seismic data almost always possesses uncertainty in the interpretation stage, with many possible outcomes. The interpreter must possess ample geophysical, geological, and in this case, oceanographic knowledge to make the best, and most likely conclusions on the subsurface structures. Where possible to acquire, knowledge of the regional tectonic setting, palaeoceanographic set-up of the margin and additional data (such as bathymetric, petrophysical and sedimentological) can aid the interpretation of the seismic data into a realistic and robust geological model.

7.2 Key Features at a Facies and Sediment Scale

Fine-grained contourite facies (muds and silts) are fairly well constrained and tend to show high levels of bioturbation, poor preservation of bedforms and gradational fluctuations in grain size that have been linked to changes in bottom current velocity (Stow et al. 2009). They are distinguished from other fine-grained deposits (pelagic and turbiditic) on account of their bigradational units and complete sediment reworking by bioturbation. Contourite *sands* however show a much wider variety of facies and facies associations, and are therefore much more difficult to distinguish from other deep water sands. Here we discuss the key features of contourite sands at core and sediment scale and how they differ from other deep water facies.

7.2.1 Contourite Sand Facies

At a sediment core scale, this study has examined sediment from various contourite depositional environments and of varying facies (Table 7.1). Facies were logged visually, and where possible, CT-imaging was used to further aid interpretation. Here, key sedimentary features within the facies are discussed and a new set of contourite facies models proposed.

7.2.1.1 Discontinuities

Throughout the 13 sediment cores logged, there is a spectrum of different facies boundaries seen from gradational, through to erosional. Abrupt and erosional boundaries often separate sandy units and are interpreted as representative of an increase in energy (bottom current velocity). There are some classic examples of the ichnofacies *Glossifungites* (e.g. Fig. 7.1) which is commonly associated with an erosional hiatus from which large-scale burrows penetrate deeply into the underlying substrate (MacEachern et al. 1992). Some erosional hiatuses in the cores have been partially homogenised due to intense bioturbation activity – but many are still clearly observed throughout the sediment. This indicates that there has been times of bottom current velocity capable of non-deposition and erosion. Distinctively abrupt erosional hiatuses are observed throughout the cores positioned closest to the main MOW bottom water channels, although some significant erosional boundaries can also be seen in the earlier sedimentary section of PC08 despite being positioned away from the modern route of the main bottom water core. Erosional discontinuities are generally associated with coarser sediment – from fine sand upwards.

Within the *channels*, amalgamated massive sands and laminated sands dominate. These are often separated by erosional surfaces representing further increased bottom current velocities. The *drift* sediments however, are dominated by massive and fine bioturbated sands and show much higher cyclicity (>0.5 m), indicating that at times bottom currents sweep over the sea bed on the drifts, but at other times there was much quieter conditions. Unit boundaries on drifts are therefore more commonly non-depositional, or gradational (often reworked by bioturbation).

Core	Water Depth (m)	Locality	Depositional Environment
BC05	738	Midslope	Contourite Channel
PC04	658	Midslope	Mounded Drift
PC06	490	Upperslope	Plastered Drift
PC08	961	Lowerslope	Mounded Drift
D13075	977	Lowerslope	Contourite Channel
D13896	817	Midslope	Mounded Drift
D13889	1580	Lowerslope	Fan Drift
D13899	1179	Lowerslope	Mounded Drift
D13900	1297	Lowerslope	Fan Drift
D13894	1538	Lowerslope	Hemipelagic
U1386	561	Upperslope	Mounded Drift
U1388	663	Midslope	Contourite Channel
U1389	644	Midslope	Sheeted Drift

Table 7.1: Depositional Environment and Sand portion of each core.

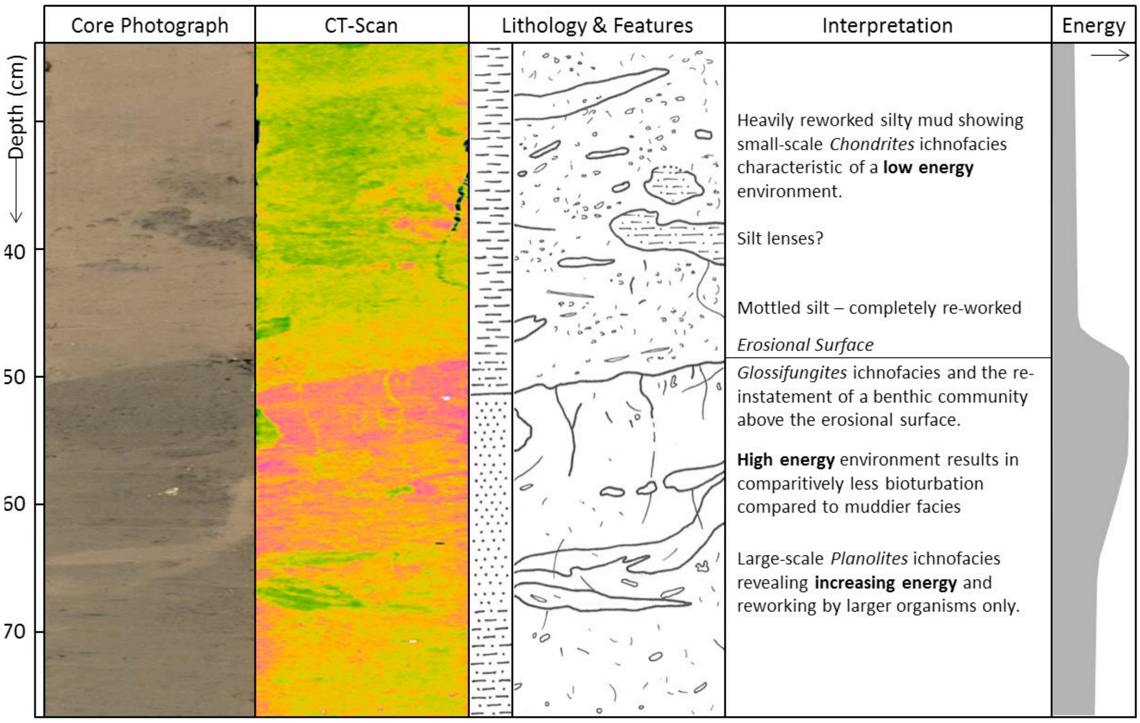


Figure 7.1: An example of the association between bioturbation, grain size, and depositional energy. Example form PC04 Trigger Core.

Discontinuities and erosional boundaries are also often associated with other deep water sedimentation processes, namely downslope turbidites and debrites. These however, have subtly different characteristics that often relate to the facies sequence. Unlike in downslope processes, the facies below an erosional boundary will rarely be muddy as this indicates an unlikely very rapid change in depositional energy from sluggish (<10 cm s^{-1}) to very vigorous (>25 cm s^{-1}) bottom currents over a short period of time (or represent the erosion of a significant thickness of the underlying unit). More commonly, a gradual increase in grain size is observed up the core (reverse grading) that represents a steady increase in bottom current velocity, up to the point of non-deposition and erosion. Above the erosional boundary, normal grading is often seen, corresponding to a waning of the bottom current. Contourites also tend to show a much wider variety of boundary types compared to turbidite sequences – from broad gradational to abrupt non-depositional to erosional. Gradational boundaries are found in finer-grained contourite sedimentary sequences and correspond to steady fluctuations in bottom currents that never reach non-depositional velocities. Abrupt changes are also seen, and these do not appear erosive, but rather indicate a rapid change in deposition type. Such boundaries are common at the transitions from silt to sand facies, and are thought to indicate some threshold from settling to bed load deposition (Thompson, P pers.comm.)

7.2.1.2 Sedimentary Structures

Contourite sands appear to be more prone to the preservation of sedimentary structures (lamination) than their finer-grained equivalents. Fine-grained contourites tend to have little to no preservation of sedimentary structures due to reworking by bioturbation (Wetzel 2008). This appears true also for fine-grained sands that show extensive reworking. This study shows that medium- to coarse sands show a significant decrease in the extent of bioturbation, and therefore have the capacity to preserve primary sedimentary structures at a core scale.

However, for most of the sandy contourites in this study there is a distinct lack of any structures, and the medium contourite sands often appear massive and structureless (Fig 5.6 F). One possible cause of this is the highly fluidised nature of the soft sediment contourite sand cores that results in the destruction of structures during the core acquisition process. For example, the uppermost section of PC06 has been greatly fluidised on acquisition and transportation due to the unconsolidated and coarse nature of the sediment. Therefore, the original sedimentary features have not been preserved in the top 40 cm. There are however, sections of sandy core at depth that appear to have been undeformed by the coring process and are absent of any sedimentary features. The mechanism for these massive sands remains an outstanding question. One possible explanation is the high accumulation rates (>100 cm s^{-1}) observed within the contourite sands in this study (Fig. 5.23). Elsewhere, there are some indications of lamination and cross-bedding but these are usually masked by extensive bioturbation in finer sands, or are relatively localised and short-lived in medium and coarse sands (< 0.5 m thick). That said, some distinct beds are seen down the cores and are generally restricted to channel sands which show signs of both lamination and cross-bedding, for example U1388 (Fig. 5.6 E).

7.2.1.3 Bioturbation Patterns

X-ray and CT-imaging are by far the best way to examine bioturbation in soft sediment cores (Wetzel et al. 2008). However, the study of contourite ichnology is still very much in its infancy (Baldwin and McCave 1999; Löwemark et al. 2004; Wetzel et al. 2008; Essex and Stow 2013) and a definitive ichnofacies model for sandy contourite deposition is yet to be developed. Although it is yet to be quantitatively examined, it appears that there is a clear link between grain size and bioturbation style. Bioturbation has long been used as a diagnostic tool for the identification of fine-grained contourite sediments (Stow and Faugères 2008). In reality of course, bioturbation of sediment can happen in any environment where: 1) the sediment rate does not exceed that of the bioturbation rate, 2) there is sufficient nutrient influx to support a benthic community and 3) the substrate composition and consistency is favourable for benthic habitation (Wetzel 1991). The presence of trace fossils is, therefore, by no means restricted to contouritic sediments. Rather, those trace fossils should be used to tell us more of the depositional regime. Table 7.2 summarises the main styles observed within the sediment from mud-dominated through to coarse sand. The trends observed in the cores in this study are broadly comparable to those observed in studies elsewhere, as outlined by (Wetzel et al. 2008) and are justified below.

Fine-grained contourites: All low-energy contourites are expected to have extremely high levels of bioturbation. Muddy sections regularly appear 100% reworked with the core surface appearing massive and structureless, with no bedforms seen even in X-ray images. Very small-scale burrows can be distinguished on the order of some millimetres in length and are chaotically orientated and cross-cutting. The intensive sediment re-working by burrowing organisms suggests that bottom water influences over the area are transporting nutrients to the sea floor. When silt enters the system, complete reworking is again common, and the sediment takes on a characteristic 'mottled' appearance.

Very fine sands: The interest of this study is the sand-rich facies. Contourite sands show a variety of ichnofacies that appear to be broadly linked to grain size. Chapter 5 outlines the range of contourite sand facies observed in the Gulf of Cadiz cores (Fig. 5.5). Very fine sands appear to have a similar facies to those observed in silt-dominated contourites: heavily bioturbated and mottled in appearance. Some indistinct burrow features may be observed, but the degree of bioturbation means that these have been cross-cut and deformed by many tiers of burrowing. Silty and fine sands indicate that there is an enhanced bottom current influence and thus an increased influx in nutrients for the benthic community dwelling on the sea floor and within the sediment. As a result, larger organisms are supported and there is a greater biodiversity.

Fine to medium sands: These are characterised by distinct large-scale burrows up to approximately a centimetre in diameter in addition to significant numbers of finer trace fossils. *Thalassinoides* and *Planolites* form spherical and elongate mud-filled trace fossils up to ten centimetres in length. These larger burrows are often subsequently cross-cut by others such as *Trichichnus* (Fig. 5.3). There are various large-scale (up to cm diameter) trace fossils that run horizontally across the sediment core which are interpreted as *Zoophycos* or seabed ploughers *Scolocia* (Fu and Werner 2000). Fine to medium sands are thought to represent an enhanced bottom current influence across the core site. This in turn is thought to create an increased supply of nutrients to the sea floor. The increasing bottom current velocity required for fine to medium sand deposition prevents small-scale organisms and juveniles from establishing, and therefore larger-scale organisms generally dominate (Wetzel 2008).

Medium to coarse sands: Where the core reaches high sand content (greater than 70 %) there is a marked reduction in bioturbation of the sediment. These facies can be laminated (Fig. 5.6 E) or structureless (Fig. 5.6 F). For clean medium- to coarse-sands to be deposited, vigorous bottom currents on the order of 50 - 100 cm s^{-1} are expected (Stow et al. 2009) and this is generally too hostile an environment for bottom feeders. Deep burrowing organisms may survive such an environment, but the removal of juvenile organisms makes it difficult for a community to sustain itself. In such sections, rare large-scale burrows are observed and there is usually a distinct region at the top of the bed where pipes intrude downwards filled with mud from the overlying unit. There are some classic examples of this ichnofacies, named *Glossifungites* (Fig. 7.1) (MacEachern et al. 1992).

Contrary to fine-grained contourites, which show intense bioturbation, the data here reveals that with increasing grain size, less bioturbation is seen in contourite sands. Very fine sands show high bioturbation rates and high fauna diversity. Fine to medium sands show a marked change in bioturbation style, with larger-scale (>1 cm diameter) or deeply penetrating burrows only. Medium to coarse sands only rarely show any trace fossils indicating that bottom currents at the time of deposition or accumulation rates were sufficiently high to prevent the habitation of the sea bed by fauna (Table 7.2).

Turbidite sands tend to be devoid of any significant trace fossils due to the instantaneous depositional nature of turbidite sands (Table 7.3). Any fauna inhabiting the sea floor will be removed with a turbiditic event passing over it, and the associated high sedimentation rate

	Mud	Silt	Fine Sand	Medium Sand	Coarse Sand
Current Regime	Low Energy				High Energy
Dominant Processes	Settling	Deposition		Winnowning	Erosion
Dominant Trace Fossils	Condrites Trichichnus Phycosiphon	⟷	⟷	Thalassinoides Planolites Zoophycos	Glossifungites
Extent of Bioturbation					
Feeding Strategy	Temporary Interface Feeding	⟷	⟷	Filter Feeding	

Table 7.2: The main styles of bioturbation observed within the contourite sediment and their association with bottom current velocity. Modified from Wetzel et al. (2008).

prevents any reworking of the sandy base of the event bed. Bioturbation may occur in the fine top portion of the turbidite succession, but only if there is sufficient time between downslope events for the re-colonisation of the sea bed. Therefore, both turbidite and contourite medium to coarse sands may appear to have similarly low bioturbation rates and care must be taken to examine the associated finer-grained facies to identify any differences (Wetzel 2008).

Detailed studies assessing bioturbation using X-radiograph and CT-images on contourite sediments are limited (Baldwin and McCave 1999; Löwemark et al. 2004; Wetzel et al. 2008). As a result, there is still much progress to be made in this area of contourite research. Some key differences in the depositional regime and resulting bioturbation rates are summarised in Table 7.3. There is still a need for a standard ichnofacies model or characteristic trace fossil assemblages for muddy and sandy clastic contourites (Bromley 1996).

7.2.1.4 Facies and Facies Sequences

Logging of the cores clearly shows a variety of small-scale facies sequences linked to grain size variations. These are also clearly imaged as density changes on CT-image data which can be used give a first examination of grain size trends (Fig. 5.2). This combination of grain size analysis and visual logging allows for a number of facies sequences to be described in the Gulf of Cadiz (see chapter 5). Here, we focus on the contourite *sands* in the cores, and their association with other facies.

The sequences show distinct cyclicity, (in the order of 0.5 m in silt and very fine sand facies, up to 2 m cyclicity in medium to course sands). The sand units rarely exceed 1-2 metres thickness, with the greatest thicknesses accumulated within contourite channels or, as with core site D13900, on fan drifts at the exits of channels (Fig. 7.2). Bed thickness is a function of sediment influx, persistence of bottom current, and erosion:deposition. This interbedding with other, more fine-grained facies, combined with the erosive nature of vigorous bottom currents, has resulted in several different facies sequences (top-cut-out, base-cut-out and bigradational sequences) (Fig. 5.7). Assuming that grain size can be broadly linked to bottom current velocity, these sequences can be explained by the changing transport capacity of currents and depositional mechanisms (suspended vs. bed load) at any one particular location.

Very fine sands appear similar to other fine-grained contourite facies: heavily bioturbated. There is a distinct lack of any primary sedimentary features, and instead, multiple generations of burrows are seen in CT-images (Fig. 7.1). The soft sediment core face often has a distinctive 'mottled' appearance. This complete sediment reworking is attributed to sluggish (< 10 cm s^{-1}) bottom currents providing enhanced ventilation and nutrients to the sea floor that promotes

	(Hemi)Pelagic	Turbidite		Contourite	
		Mud	Sand	Mud	Sand
Sediment Accumulation	Continuous slow	Instantaneous rapid	Instantaneous rapid	Semi-continous deposition and reworking	Intermittent – deposition and reworking
Organic Matter Influx	Vertical flux	Vertical flux and suspension transportation	Vertical flux and suspension transportation	Vertical flux and lateral input	Vertical flux and lateral input
Fauna Stability	Continuous	Killed and decolonised with turbidite events	Killed and decolonised with turbidite events	Continuous	Poor: deep-burrowing organisms may survive
Fauna Abundance	Average to low	Varied depending on turbidite events	Low	Very high	Fine Sands = high Coarse Sands = Low
Bioturbation Rate	Average. Controlled by vertical flux	Generally low	Low	Very high	Fine Sands = high Coarse Sands = Low

Table 7.3: Expected biotubation patterns across the different deep water depositional environments. Modified from Wetzel et al. (2008)

benthic communities. The very fine sand facies are often associated with other, finer-grained facies by gradational boundaries, and tend to be restricted to contourite drifts.

Fine sand facies also show evidence of bioturbation, although the ichnofacies appear very different (Fig. 5.6 D). Larger burrows tend to dominate, reaching over 1 cm in diameter. Locally, some evidence of lamination may be seen as a result of less-extensive sediment reworking by bioturbation. This change of ichnofacies is due to the increasing bottom current velocities required for fine sand deposition. More vigorous currents prevent habitation of the sea floor, as small organisms and juveniles are swept away. Therefore, it is only larger species, and deep penetrating burrowers that are able to survive (Wetzel 2008). Fine sands are often associated with other, finer grained facies by gradational boundaries, and may show hiatus or non-deposition surfaces. They tend to be found on contourite drifts.

Medium - coarse sands show an array of different features. *Massive sands* are seen most commonly (Fig. 5.6 F), and have been collected from both drift and channel-fill sediments. They are broadly structureless, although can contain lenses of coarser material. These lenses are localised features perhaps related to a scour or obstruction (such as a crag and tail structure). Modern examples are seen on sea floor photographs from contourite channels in the area (Stow et al. 2013b). The boundaries between this and other facies are often abrupt and erosional. In some cases amalgamated sands are seen (as in channel fill deposits at core site U1388) which can significantly increase the thickness of sandy facies. More rarely seen are *laminated sand facies* (Fig. 5.6 E). These are mainly only seen in channel locations, and the unit of preserved laminations generally doesn't exceed 50 cm in thickness.

Contourite sand facies of significant thicknesses are accumulated within the contourite channels and there is a marked reduction in sand content laterally away from channels (with respect to net-to-gross and mean grain size). The importance of the contourite channels is illustrated in Figures 5.1 and 7.2. When facies sequences are plot against water depth and distance from the Gibraltar Gateway. Sand facies are able to travel great distances to significant water depths when bottom currents are contained by contourite channels (e.g. core D13900 at 1297 m water depth). The lateral reduction in grain size away from bottom current cores and/or associated channels could be used to map past bottom current routes where data resolution is sufficient (Viana et al. 2007).

It should be noted, that the Gulf of Cadiz system is a mixed silci-bioclastic system, and the response in other systems may differ. For example, a carbonate contourite will have different clast transport thresholds, and therefore a different response to bottom current fluctuations.

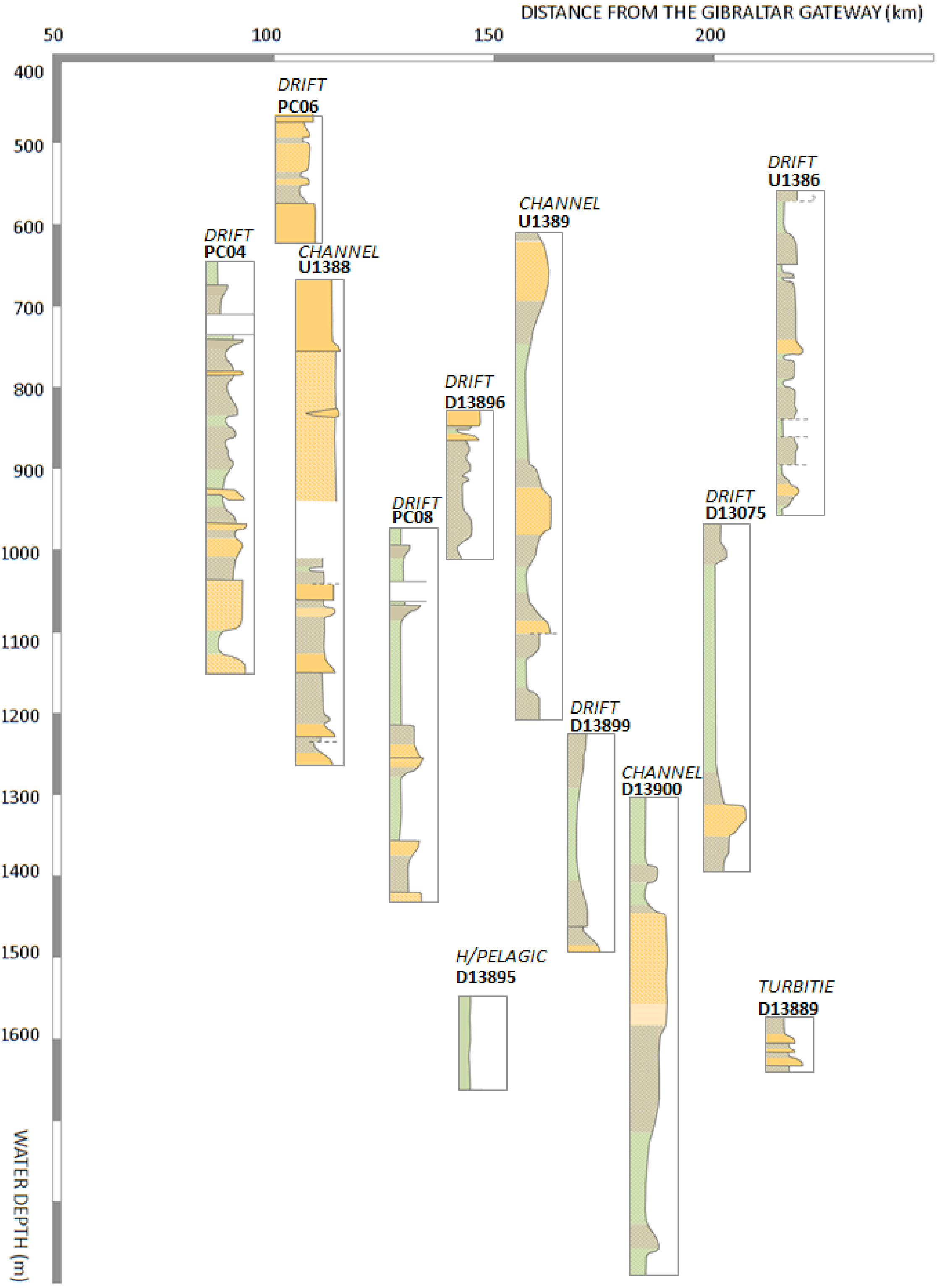


Figure 7.2: Facies sequences observed in cores logged up to 9 m below the sea floor. Plotted against water depth and distance from the Gibraltar Gateway.

The key interpretations from the analysis of contourite sand facies and facies sequences are;

1) X-ray or CT-imaging is required to fully assess contourite facies within soft sediment cores.
2) Contourite sands in the Gulf of Cadiz rarely exceed 1 m in thickness unless located within, or at the exit of contourite channels (where thicknesses up to 2 m are observed).
3) There is a link between grain size and ichnofacies where very fine sands show complete reworking and a mottled appearance, fine-medium sands are characterised by large-scale burrows, and medium-coarse sands are largely void of bioturbation structures.

7.2.2 Contourite Sand Sediment Textures

This study presents one of the largest records of sedimentological data in any contourite sand system to date. Grain size analysis of over 700 samples in the eastern Gulf of Cadiz were used to provide a good insight to the textural characteristics of all the contourite facies (muddy to coarse sand). The mean, modes, standard deviation, skewness and kurtosis have been used to look for any characteristic trends that may reveal information about depositional processes and sediment supply.

7.2.2.1 Mean Grain Size

The Gulf of Cadiz sediment samples show mean grain sizes from 6 µm to ~1000µm (chapter 5). The results were predominately used to aid facies identification and cross plot data analysis. It is seen that there is a systematic deceleration of grain size away from the Gibraltar Gateway, except where additional morphological forcing such as diapiric ridges or channels are found to accelerate the bottom current (Fig. 5.1). Despite the Gulf of Cadiz contourite depositional system being very sand-rich, there is a significant reduction in mean grain size away from the main bottom water cores, and drifts remain very mud-rich. We can therefore say that there is a strong link between mean grain size and bottom current velocity. There can, however, be no *linear* link for a number of reasons;

1. The finest portion of the sediment grains (the muds) are most likely transported as flocculated particles that are disaggregated during the grain size analysis. The finest sections cannot, therefore, show a linear relationship between grain size and depositional velocity (McCave 1984).

2. Larger grain sizes are often represented by biogenic tests such as foraminifera which are significantly lighter than a comparable clastic grain and require lower velocities for transportation (McCave 1984).
3. The semi-continuous nature of bottom currents causes prolonged erosion and winnowing that result in the recorded sediment not necessarily accurately representing the bottom current conditions at the time of original deposition (Stow et al. 2012).
4. Sediment influx and distance of transportation also play an important part (Stow et al. 2008).

Despite this, there is a broad trend of focused sand accumulation in the parts of the system where bottom water is accelerated (within channels) or where the bottom water core suddenly decelerates (at the exit to a gateway, channel or other morphological feature). Detailed work by McCave (1984) has provided a robust calculation of the relationship between mean grain size and velocity with respect to transport and deposition of sediments (Fig. 7.3).

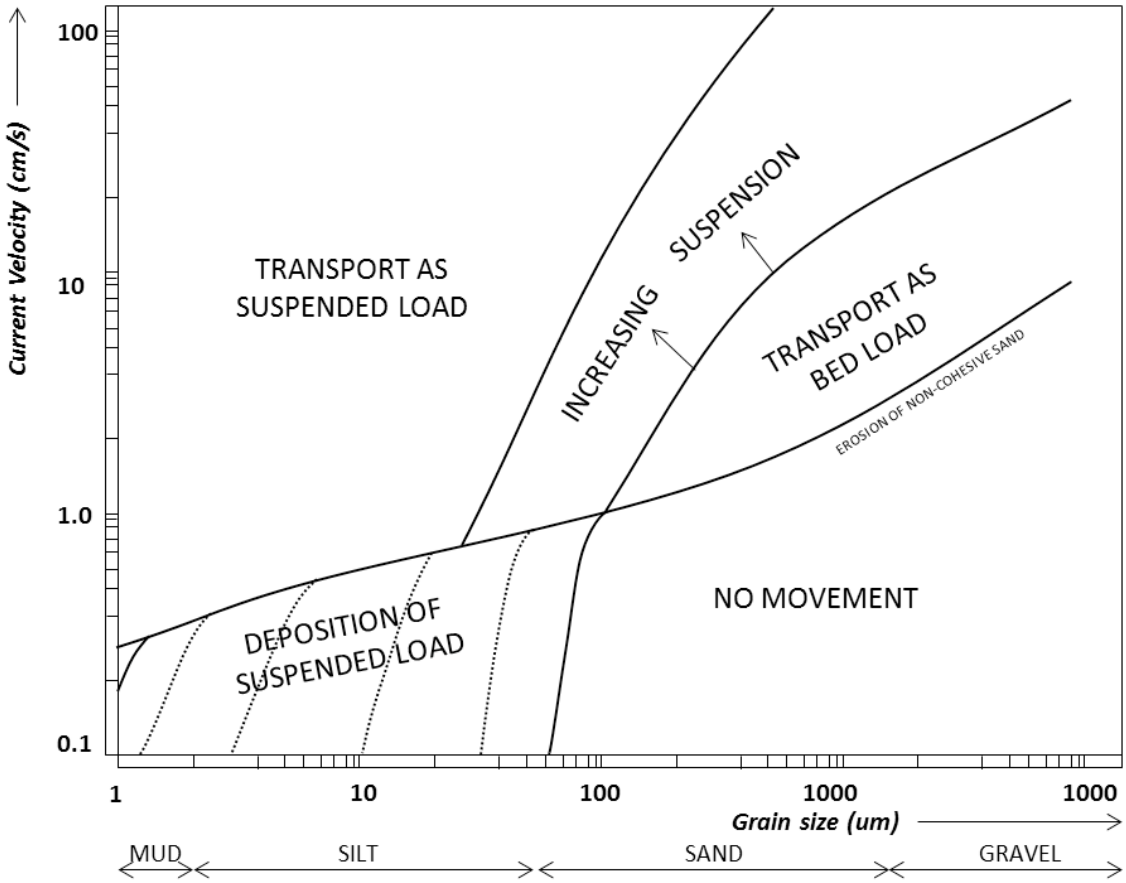


Figure 7.3: The transport and deposition of sediments. Grain size is plotted against current velocity. From McCave (1984).

7.2.2.2 Sorting

Previous studies have shown that contourites tend to be poorly sorted on account of sediment mixing by bioturbation (Wetzel et al. 2008). However, the data shows some sections of moderate sorting, and these appear to be broadly linked to mean grain size. Assessing sorting vs. mean grain size (Fig 7.4), a number of trends can be seen. Up to approximately 20 µm mean grain size, there is a *decreasing* trend in sorting. Above 20 µm however, sorting *increases* with grain size. Data points representing medium sands (collected from BC05 on the CONTOURIBER I cruise) plot off trend.

Assessing the sorting vs. grain size relationship for each core reveals that there may be a relationship with depositional process and sediment source, as different core sites show different responses (Fig. 7.4). Data points from PC04 and PC08 are on the same trend. The acoustic data shows both core sites are located on the same drift, and when the core facies are examined, it is seen that some beds can be correlated between the two core sites (chapter 6). Therefore they are expected to have similar sediment provenance, depositional processes, and sedimentary characteristics. PC06 data points are on a similar trend, but separated from the other data points. This is explained by differing sediment provenance between the core sites as evidenced by compositional data. PC06 also shows a distinct cluster of points with increased sorting that correlate to unit 1 of PC06 and may suggest a slightly different depositional process (Fig. 7.4) such as increased winnowing. BC05 also plots as a separate cluster on account of its large average grain size. It shows much better sorting than its very fine sand and silt equivalents. This marks a move towards erosional (winnowing) processes at this core site.

The trends can be broadly explained on account of the sediment supply available to the system, and the rate of bioturbation seen in each facies. Very fine grained contourite sediments are influenced by weak bottom currents that supply fine grained material. The sediment is completely reworked giving it poor sorting, but very little additional coarser grains can reach the system to decrease the sorting further. Coarse silts and very fine sands show the worst sorting. Here sediment reworking by bioturbatuion not only mixes the sediment being supplied by the bottom current, but often introduces mud and sand from over/underlying facies into the bed (e.g. as is seen in Fig. 7.1). This has dire consequences for the sorting of the sediment. It is not until bioturbation reduces with increased bottom current velocites (fine sands) that sorting improves.

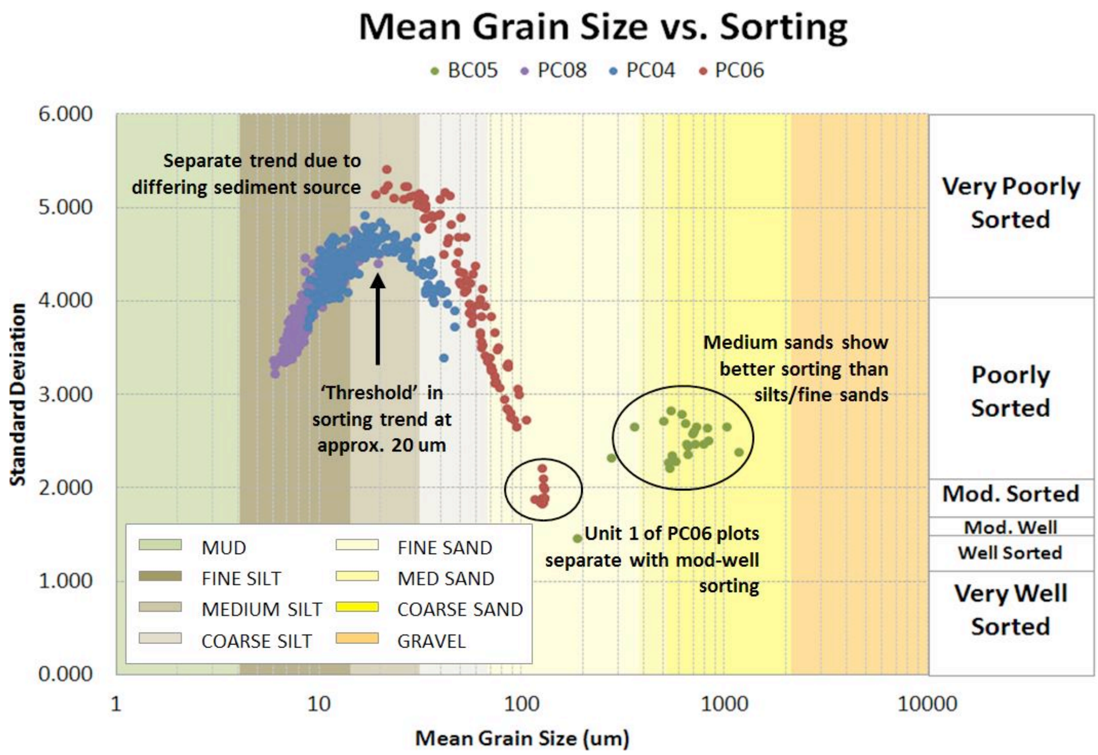


Figure 7.4: Cross plot of the sorting against mean grain size reveals that the finest sediments have a negative relationship with sorting and medium silt to fine sand has a positive association with sorting. Sorting definitions given by Folk (1964).

7.2.2.3 Skewness

As with the sorting, the skewness results from the grain size analysis also show some striking trends when cross plot with mean (Fig. 5.16 B) and first mode grain size (Fig. 5.18). There are a very limited number of studies that specifically describe contourite sand skewness (Lovell and Stow 1981; Stow et al. 1998; 2002c) and here it has been suggested that skewness can be used to aid interpretation of contourite sands. The relationship between skewness (and kurtosis) with depositional environment is poorly understood when compared to the mean and sorting (Kranck and Milligan 1991). That said, there is clearly some relationship between skewness and bottom current conditions. The muds and silts collected from the study area show near normal distributions (Fig. 5.16 B) that are characteristic of sediments deposited by settling processes, i.e. hemipelagic deposition or very fine grained contourites influenced by weak (<10 cm s^{-1}) bottom currents. Increasing grain sizes to coarse silts and fine sands show a progressively more fine skewed distribution which is characteristic of a depositional environment and where floccing is prevalent.

Skewness data is particularly valuable when cross plot against sorting (Fig. 7.5) (Martins 2003) and the control of grain size can be imaged clearly. From the cross plot, the 'ideal' distributions can be identified based on the knowledge of depositional environment (chapter 6). A distinct cluster of data points is observed in the coarse sand. These show a coarse to very coarse skew, and poor to moderate sorting. Based on analysis of depositional environment (chapter 6), these are contourite channel sands, and provide a good example of high energy contourite sand grain size distribution. The coarse skew is attributed to vigorous bottom currents winnowing away the fines, effectively removing the fine section of the grain size distribution curve and leaving the bedload remaining. The vigorous nature of the bottom currents has prevented organisms from inhabiting the sediment, except perhaps for some larger, deep burrowing species. As a result, bioturbation is significantly lower than finer-grained contourites and mixing by bioturbation is comparatively less. These sands therefore have better sorting than finer-grained contourite sediments.

At the other end of the grain size spectrum, muddy and fine silts are shown to have a symmetrical (normal) grain size distribution and poor sorting (Fig. 7.5). Analysis of the depositional environment for these data points (chapter 6) shows that they are re-worked hemipelagic or very fine-grained contourites with a mainly hemipelagic settling supply. The symmetrical distribution is attributed to the dominance of sediment settling rather than lateral bed load transportation. They are poorly sorted on account of the settling process and enhanced mixing by bioturbation.

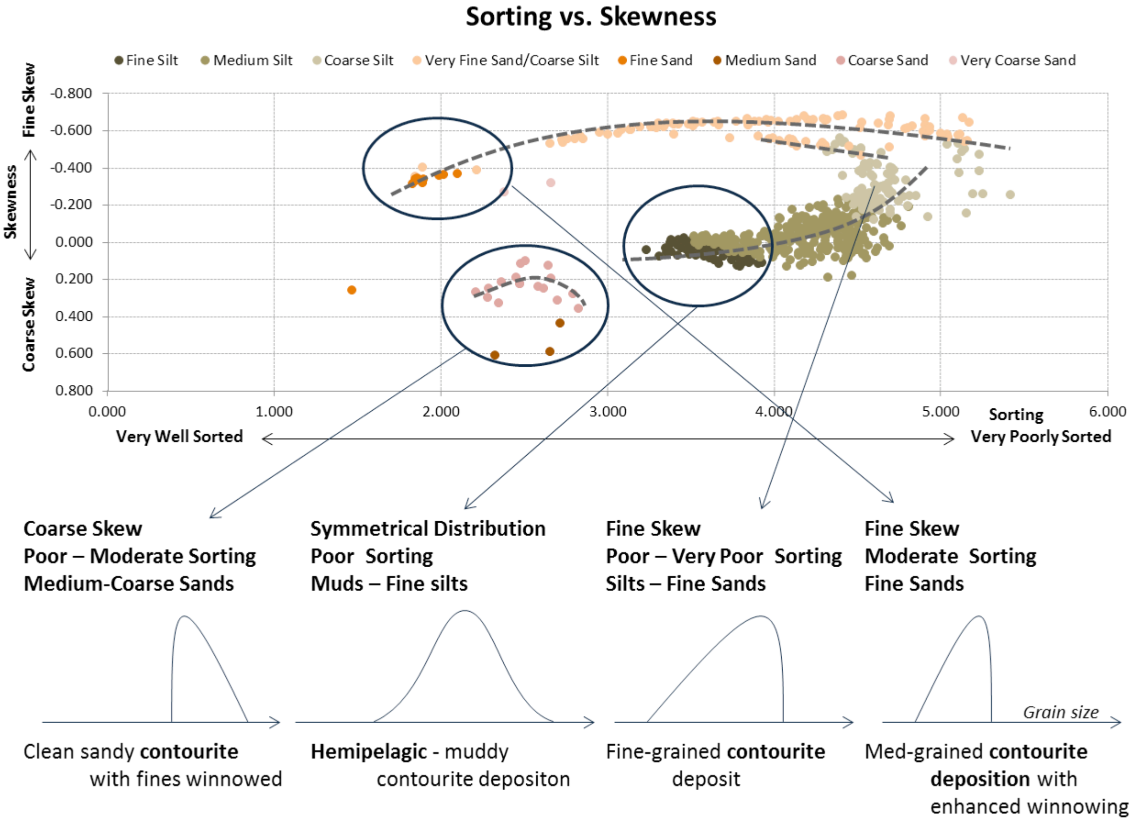


Figure 7.5: Sorting vs. skewness cross plot showing multiple trends. Data points are colour-coded with respect to mean grain size, and there appears to be a link between cross plot trends and mean grain size. See text for explanation.

The majority of the other data points show a fine skew, and poor to very poor sorting. They plot along a number of trends that broadly appear to be linked to grain size (Fig. 7.5). Silts plot along a trend of decreasing sorting and increasing fine skew as the sediment coarsens. Within the very fine sands there are two near-parallel trends. This is thought to represent two different sediment sources with slightly different provenance characteristics. All these sediments are interpreted as contourite drift sediments and their distribution is thought to be representative of dominantly depositional processes with a mixture of hemipelagic and alongslope sediment supply. Minor differences in the trends (for example the two very fine sand trend) may be attributed to additional controls such as the duration of bottom current influence on the sediment (which will also affect the bioturbation mixing rates). This is an area for further work.

There is a distinct cluster of fine-grained sands that show the highest degree of sorting and are quite separate from the other data points and are derived from unit 1 of PC06 (Fig. 7.5). These sediments show a fine skew and moderate sorting and are interpreted to be reworked sediments derived locally from the shelf. Such sediments are expected to have better sorting than contourites on account of their high energy and rate of deposition that prevents bioturbation-related mixing. They plot on the same trend as very fine sands and this, along with compositional evidence (chapter 6), allow us to interpret these as a contourite plastered drift deposit with locally-sourced sediments form the continental shelf. The cross plots in this study show that there is a strong link between grain size and the other parameters. We can therefore state that velocity is a strong control on grain size distribution. Since both skewness and kurtosis are parameters that are "*sensitive to geological processes*" (Friedman and Sanders 1978) this indicates multiple depositional processes and controls were responsible for the sedimentation in the study area.

7.2.2.4 Cumulative Frequency Curves

Figure 7.6 shows cumulative frequency curves for all the samples from the CONTOURIBER-1 cores as divided by their *average* grain size. The graphs show considerable changes in the shape of the curve depending on the average grain size and this is attributed to changing transport mechanisms (Stow and Faugères 2008). Sediment transport has been divided into suspended load and bed load. There will, of course be some component of transport of dissolved matter which can be excluded from this discussion. Bed load (Fig 7.7) is further divided into sediment transport by saltation (whereby sediment is transported by low hops along the substrate) or by traction mechanisms (rolling or sliding along the substrate) (Fig. 7.7) (Bagnold 1973).

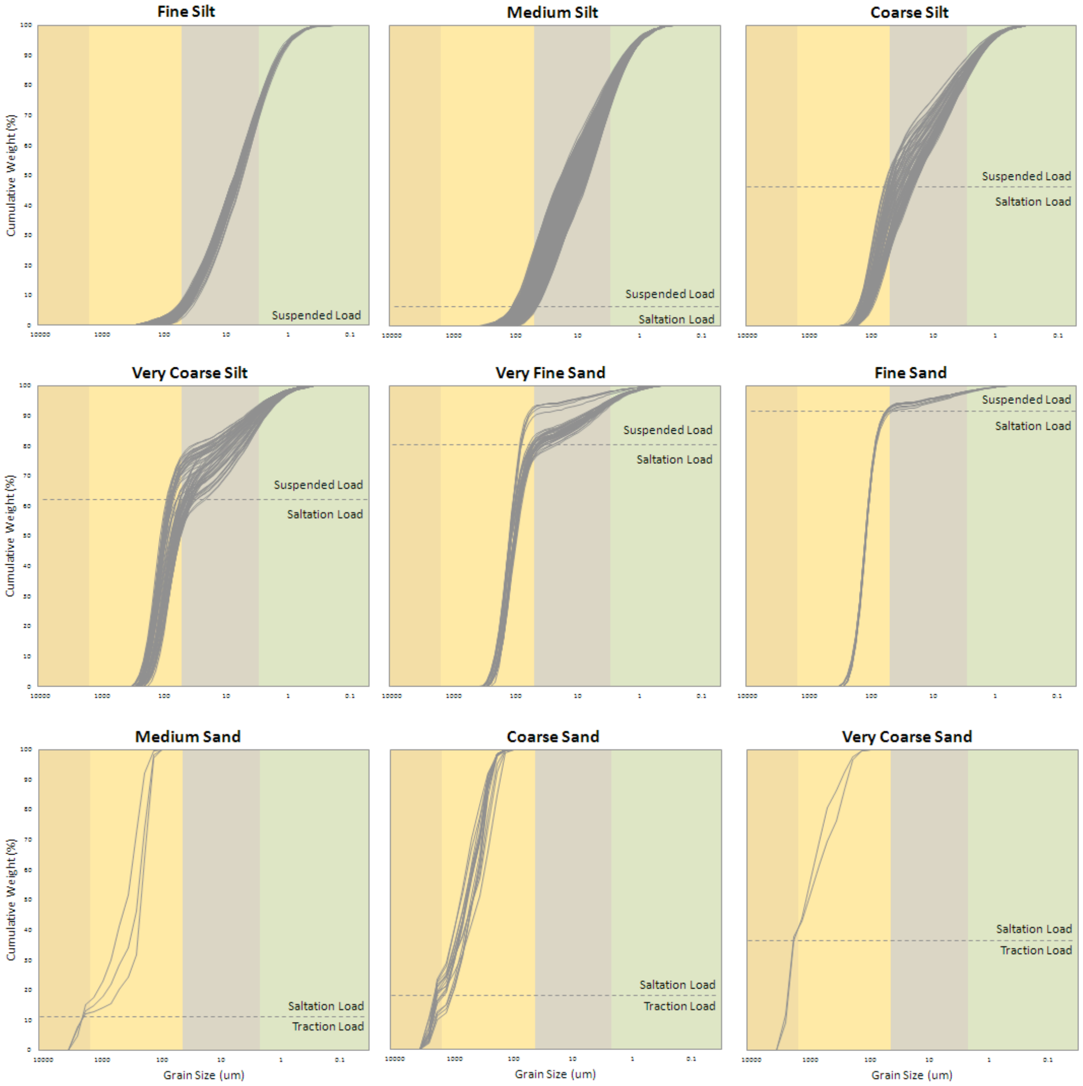


Figure 7.6: Cumulative frequency curves for each average grain size division across all CONTOURITBER-1 gravity core sites. The curves show an important change in the dominant transport process between fine silt and very coarse sand as represented by a change in the trend of the curve.

Finer sediments show a characteristic curve for suspended material deposition (Fig 7.6). With coarsening sediment comes a larger saltation component to the transport mechanism indicated by a change in the shape of the distribution curve. Fine sand is beginning to show a traction (rolling or sliding) component, shown by another change in curve gradient, but saltation mechanisms dominate (Friedman and Sanders 1978; Stow et al. 2008). This indicates that silt and mud-sized particles are winnowed away and deposited elsewhere in the system. It can therefore be said that contourite sand deposition is controlled by different sediment transport mechanisms than finer-grained contourites. Very fine – fine sands still have a considerable suspended load component, but medium and coarse sands are predominately deposited by bed load sediments (travelling by saltation or traction) and should therefore show very different characteristics.

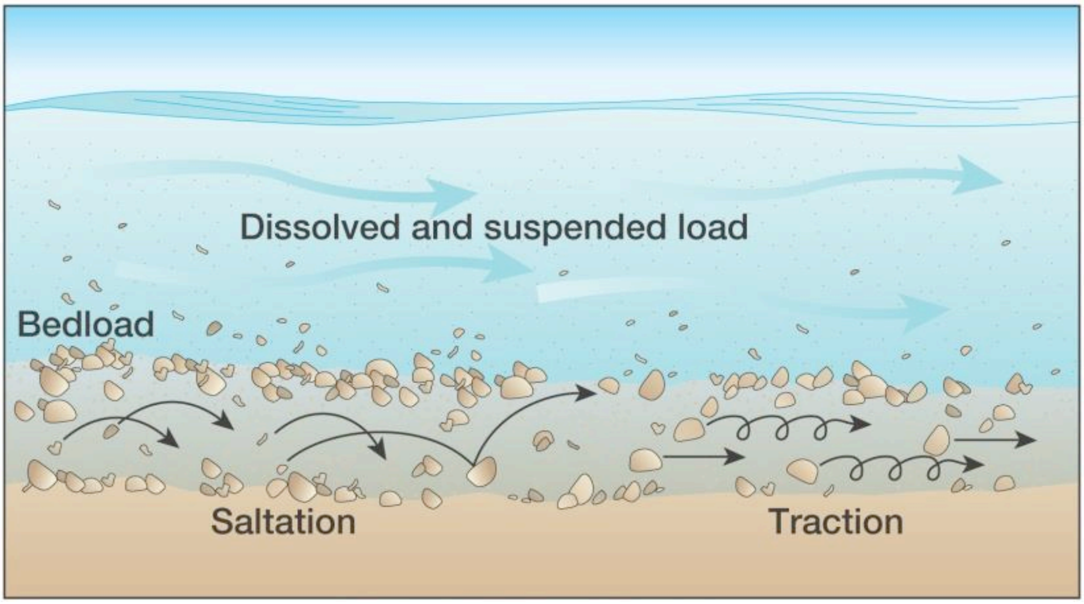


Figure 7.7: Mechanisms for sediment transport within bottom currents. (Newman 2007).

7.2.3 Discussion

7.2.3.1 Towards a New Facies Model

Compilations of logged fine-grained contourite facies from drifts around the world have led to the development of the widely recognised standard contourite sequence, first developed by Gonthier et al. (1984) and modified by Stow et al. (1986); Stow and Faugères (2008) (Fig. 7.8). It provides an end-member model for fine-grained contourite facies sequences as based on an extensive compilation of data and seen repeatedly in both modern and ancient examples. The bigradational grading is thought broadly to represent bottom current velocity fluctuations with the coarsest grains, division C3, representing the maximum velocity.

Contourite sands appear to show a much wider variety of facies and facies associations than fine-grained contourites, and also very different characteristics when compared to turbidite facies (Fig. 7.9). A variety of contourite sand facies are observed within the Gulf of Cadiz that broadly appear to be linked to depositional environment. As with other deep water depositional processes, one standard facies model is insufficient to accurately represent the range of facies observed. Therefore, a set of facies models has been proposed that range from fine-grained contourites to gravel-lag coarse contourites (Fig. 7.9). Some of the key differences between contourites and downslope facies are clearly observed when facies models are compared (Fig. 7.9).

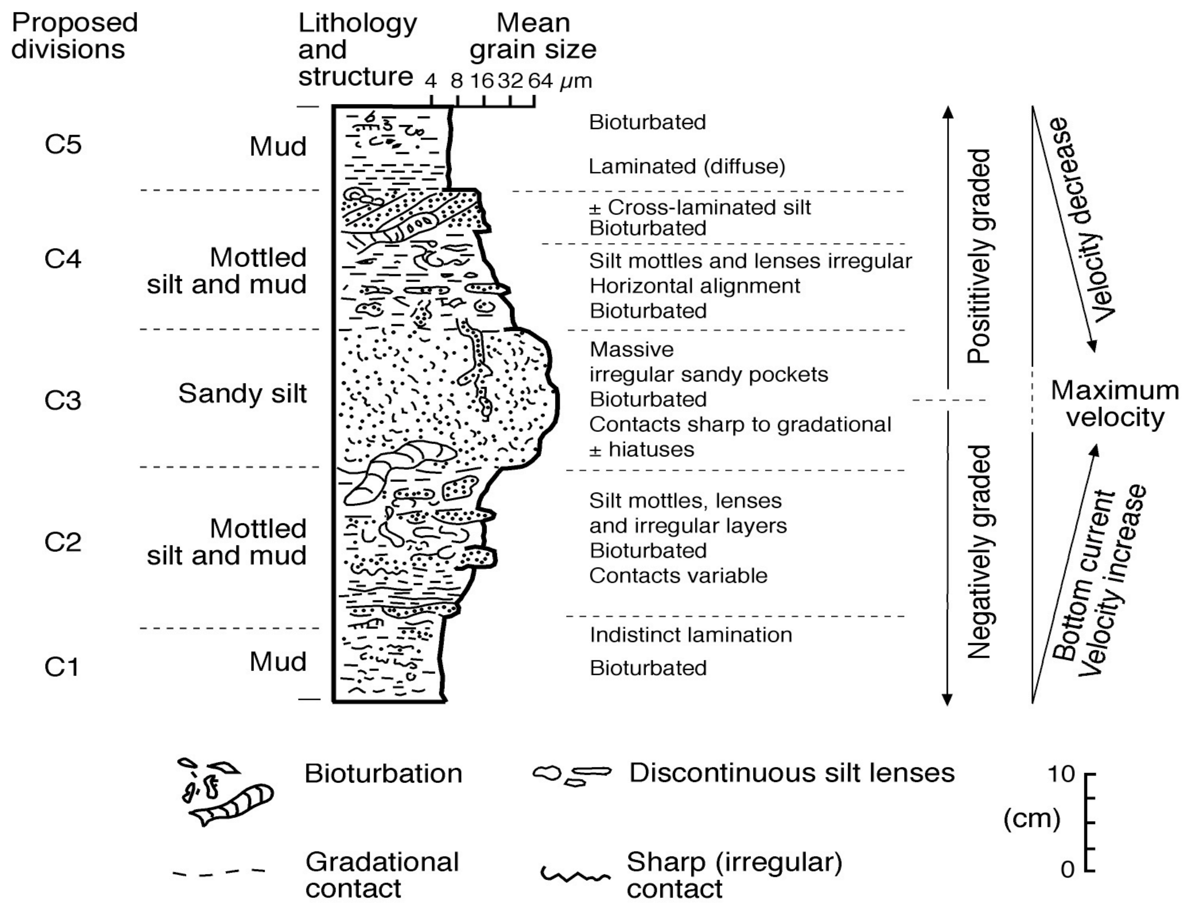


Figure 7.8: The contourite facies sequence from Gonthier et al. (1984) and modified by Stow and Faugères (2008); Stow et al. (1986).

Fine-grained contourites (mud-dominated) show little to no erosional boundaries, but rather gradational changes between muds, silts, and even very fine sands. They are very extensively bioturbated with a wide range of trace fossils often cross-cutting each other. Often, the sediment is completely reworked. Despite this, there is a high level of cyclicity in the sediment, relating to fluctuations in bottom current velocity, bottom water core location, and sediment supply. Sediment sorting is poor on account of the level of mixing by bioturbation. These features are distinct from comparable fine-grained turbidites which typically show sedimentary structures throughout, distinct erosional basal boundaries, and fining upwards (normal) grading (Fig. 7.9).

Medium-grained contourites (silts to very fine sands) have here been classed as the ‘standard contourite facies model’ (Fig. 7.8; 7.9). It is comparable to the idealised Bouma Sequence of turbidite facies models, where the full range of fine to medium sediment features is documented (although in reality, rarely are all the components seen in a single facies sequence). The contourite model shows bigradational grading (reverse then normal) with generally gradational boundaries. Some erosional surfaces may be found within the coarsest

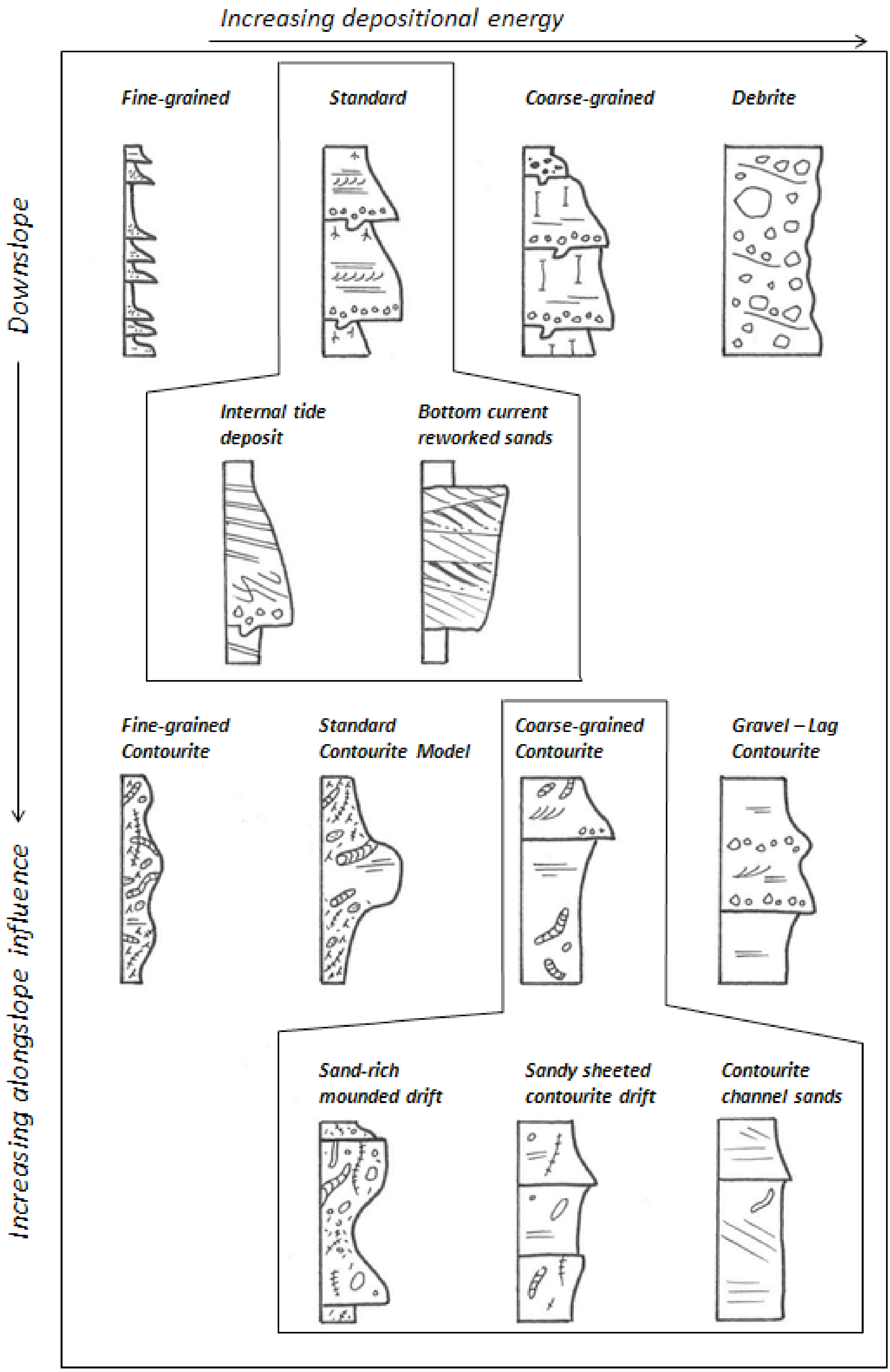


Figure 7.9: Deep water sediment facies as divided by depositional process and energy. Vertical scale approx. 50 – 100 cm. Turbidite models modified from Talling et al. (2012) and internal tide / bottom current reworked sands modified from Shanmugam (2012b).

sediment in the sequence (Fig. 7.8 C3). The variation in grain size is linked to long-term fluctuations of bottom current velocity. Small-scale cyclicity may be observed within the sequence as subtle changes in grain size. Fine sands can make up the coarsest section of the facies sequence, and these rarely exceed 1-2 metres thickness. These facies are generally poorly sorted to very poorly sorted on account of mixing by bioturbation. This differs from the turbidite facies model on many counts (Fig. 7.9). Firstly, the Bouma Sequence shows stacked normally-graded sequences with erosional bases. Sedimentary features (lamination and cross bedding) are common up the sequence, and a mud cap can show minor or major bioturbation depending on the time between turbidity events.

For *coarse-grained contourites (*medium to coarse sands), no single model can be applied as there are a range of sand facies observed that broadly link to bottom current intensity and depositional environment. Figure 7.9 shows three distinct facies models for medium – coarse grained contourite sequences, one for sand-rich contourite mounded, or plastered drifts, one for high-energy sandy sheeted drifts and one of contourite channel facies. There is a marked reduction of bioturbation compared with medium-grained contourites, although where present it is large-scale. Erosional and non-depositional surfaces are common, along with lenses and layers of coarser sediment. Some rare examples of laminated and cross-bedded contourites are seen in coarsest sands (Fig. 7.9). They differ from coarse-grained turbidite faces by their lack of any normal grading, the rare presence of large scale trace fossils, and their lack of any water escape structures (Fig. 7.9).

Finally, although *gravel lag facies* were not observed within this dataset, they have been seen in other studies in the Gulf of Cadiz (Stow et al. 2013b). Unlike downslope mass wasting deposits (debrites), these gravel facies tend to be short-lived, very laterally constricted, and finer grained on account of the large amount of energy required to transport such grain sizes (Fig. 7.9). They rely on sediment sourcing and abnormally vigorous bottom currents and they are observed at a seismic scale located only within contourite channel systems.

7.2.3.2 Towards a Contourite Sediment Textural Model

The grain size data in this study shows a wide range of distributions, and using additional data (chapter 6) these can broadly be linked to depositional environment (Fig. 7.10). Contourites are seen to have changing grain size distributions depending on their mean grain size. Very fine-grained contourites show a large standard deviation (poor sorting) and a near symmetrical distribution. This is similar to pelagic and hemipelagic sediment grain size distributions, however the standard deviation is likely to be larger in fine-grained contourite sediments on account of increased sediment mixing by bioturbation. Silt and fine sand-dominated contourites show poor to very poor sorting (a very large standard deviation) and tend to have a fine skew. The reason for this fine skew is probably due to the flocculation of clays. These flocs are disaggregated during the grain size analysis procedure to reveal a fine tail of sediment. Turbidites are also expected to show a fine skewed distribution, but sorting is expected to be better due to the relative lack of bioturbation and settling transport mechanism. Finally, coarse-grained contourites (medium sands) show poor to moderate sorting and a coarse to very coarse skew that is attributed to winnowing of fines by vigorous bottom currents and a reduction in mixing by bioturbation.

In reality, there is a continuum between processes and mixed systems will occur. Distribution is also strongly controlled by sediment provenance and some processes result in distributions that are very similar to others. Therefore, we conclude that grain size parameters cannot be used *alone* to identify contourite sands and distinguish them from other depositional processes, but rather act as an aid when building evidence for positive identification when used with facies and acoustic information.

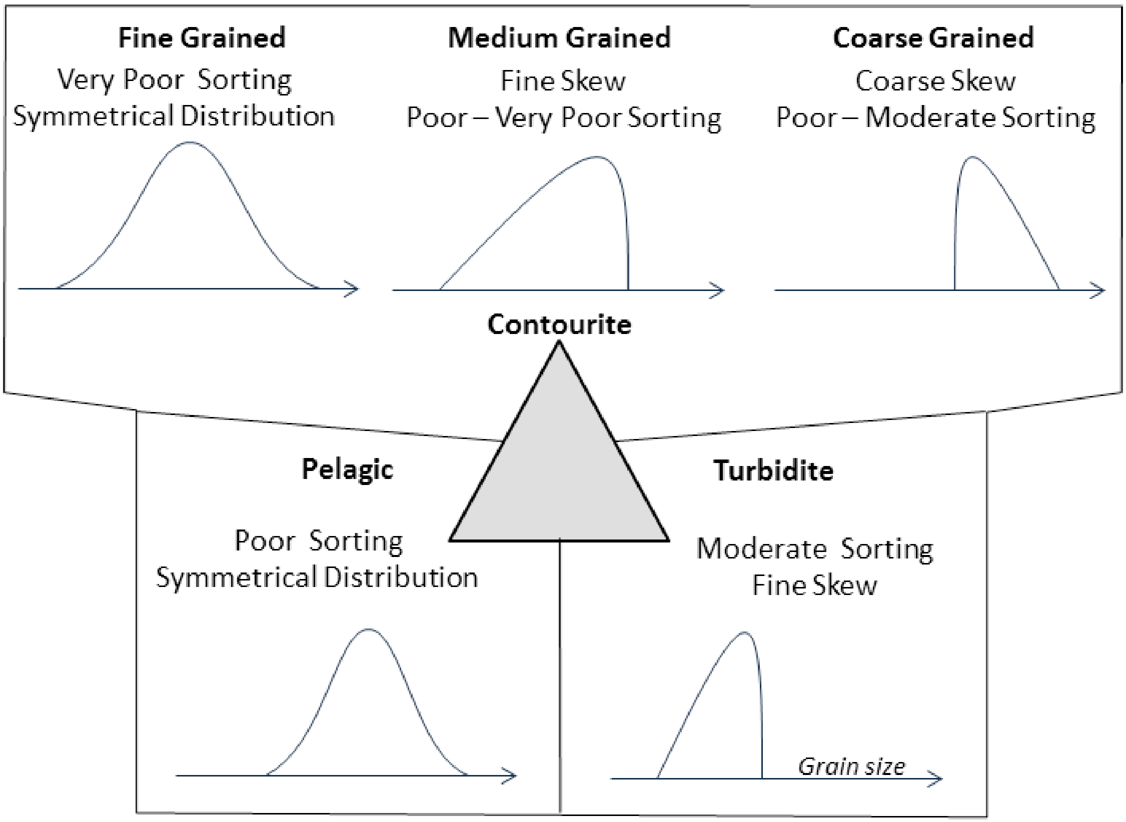


Figure 7.10: End-member models of grain size distribution as expected for each depositional process acting in deep water. In reality, there is a continuum between processes and mixed systems may occur. Distribution is also strongly controlled by sediment provenance.

7.2.3.3 Other Deep Water Sand Facies

Contourite deposition rarely occurs in isolation. Even under the influence of the vigorous MOW in the Gulf of Cadiz, evidence for other depositional processes is seen in the seismic and sediment data (chapter 6). Here we assess interbedding facies and bottom current reworking to assess how they can be distinguished using examples from the Gulf of Cadiz and further afield.

The contourite sands observed in the Gulf of Cadiz are deposited by a *thermohaline-driven* bottom current. The features seen in this study are also observed in deposits of other thermohaline-driven bottom current deposits such those studied by Nelson et al. (1993), Viana et al, (1998), Akhmetzhanov et al. (2007), Moraes et al. (2007), Masson et al. (2010), and Stow et al. (2013b). In all these examples, contourite sands show gradational facies transitions, limited bedform features and bioturbation as is seen in mud-rich contourites. Elsewhere, bottom current sands can be deposited from other oceanographic currents such as wind-driven currents, internal tides, internal waves, benthic storms and tsunamis. The resulting sediment facies can look very different and care should be taken not to apply the conclusions of this study to systems that have very different controls.

Where downslope and alongslope processes are synchronous, and currents reach sufficiently vigorous velocities, *bottom current reworked sediments* are formed (Fig. 7.11). In the Gulf of Cadiz, it could be argued that the upper slope core site PC06 contains some such deposits where sediments derived locally from the shelf are periodically reworked by alongslope currents. The extent of reworking is dependent on the velocity, and therefore the transport capacity, of the bottom current. Of particular interest are winnowed turbidite deposits (Shanmugam 2006; Mulder et al. 2008). They can occur where a downslope turbidite channel-levee system is formed under a bottom water core pathway. The current can pirate fines from the turbidite overspill plume and redistribute them alongslope (Fig. 7.11). The up-current levee effectively becomes starved of sediment, whereas the down-current levee becomes oversized, often leading to impressively asymmetric channel-levee systems such as those seen in the Weddell Sea (Michels et al. 2002). In other cases, the bottom current can deflect the downslope sedimentation obliquely of alongslope as is seen along the Brazil (Moraes et al. 2007) and the French Margins (Savoye et al. 1993). Evidence for interaction may also be seen at a facies-scale as modified turbidites (Stanley 1993). Such beds may show normal grading as is typical with downslope sediments, but with a contourite re-worked cap (Mulder et al. 2008). Examples of such deposits exist from the Columbia Channel offshore Brazil (Faugères et al. 2002b) and Kazusa Forearc, Japan (Ito 1996).

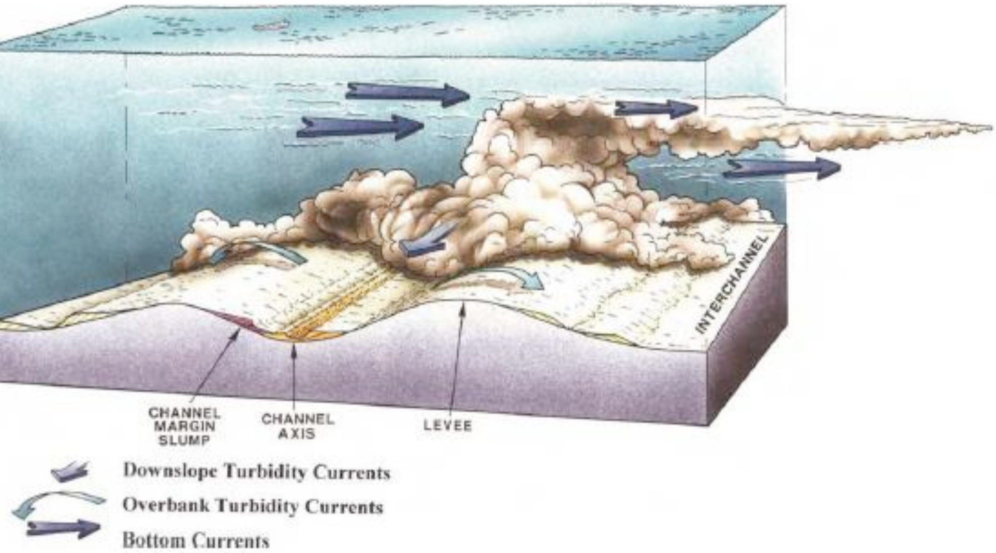


Figure 7.11: Reworked turbidite sediments occur where downslope sediment influx crosses the path of bottom currents. Where bottom currents are sufficiently vigorous, sediment pirating and reworking occurs. Figure from Shanmugam (2006).

At even higher bottom current velocities, erosion, and the complete removal and redistribution of incoming downslope sediment may occur as is seen along the Pliocene of the Algarve margin of the Gulf of Cadiz. This will be evidenced on seismic by laterally-extensive erosional surfaces and in sediment core by sharp erosional surfaces, hiatuses and hard-grounds. The pirated and eroded sediment will be re-deposited elsewhere in the basin where the transport capacity of the current is diminished. Where only the fine portion of the downslope sediment influx can be pirated (the fine sediment portion of a turbidite plume or shelf spillover sediments), the sand portion remains and can be relatively well sorted compared to other contourite or turbidite sand bodies. Such depositional environments are becoming more important to understand for the hydrocarbon reservoir potential of contourite sands (chapter 9).

These mixed systems, or bottom current reworked sands have been extensively studied in the Gulf of Mexico (Shanmugam et al. 1995; Shanmugam 2006; 2012b). Core photographs show bedforms, traction surfaces and mud drapes (Fig. 7.9; 7.12 A). Such features have also possibly been observed in the examples identified in Asia (Youbin et al. 2008; 2011) although their origin is still under dispute (Shanmugam 2012a). These differences in facies are thought to be due to;

1. The different origin on the bottom currents affecting the area. The Gulf of Mexico is influenced by a wind-driven current and therefore it does not provide the same level of nutrients to the sea bed as thermohaline currents (those currents that originate at

the sea surface and rapidly descend to the sea bed through density contrasts). As a result, wind-driven currents are relatively nutrient poor and do not promote enhanced bioturbation. Therefore bedforms are most likely to be preserved;

2. The nature of wind-driven currents when compared to thermohaline geostrophic currents is much more varied over time. True contour currents are quasi-steady over geological time, and notable velocity changes are linked to climatic cycles on the order of 100,000s of years. Wind-driven currents are much more variable and shorted lived as they are dependent on the local continental morphology and short-term climatic and meterological fluctuations;
3. The interplay between downslope and alongslope sedimentation in the Gulf of Mexico is different compared to the Gulf of Cadiz, with high sediment influx through downslope processes being modified by bottom currents. High sedimentation rates in the Gulf of Mexico confirm that a huge volume of sediment is delivered via the Mississippi, Brazos and Rio Grande Rivers that drain the American Continent. The Gulf of Cadiz is a much more alongslope-dominated margin. Other examples from the Atlantic Ocean show that downslope processes can be much less important for sediment supply.

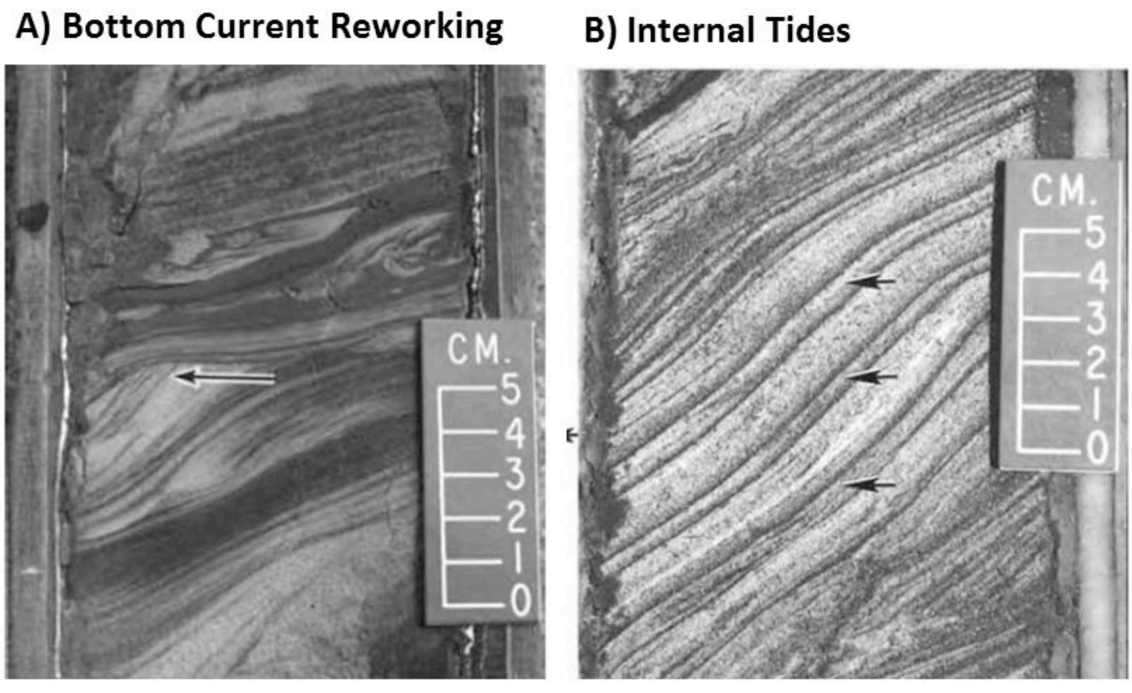


Figure 7.12: Other sand facies deposited by bottom currents. A) Deposited by the wind-driven Loop Current of the Gulf of Mexico. Photograph shows multiple bedforms and characteristic 'mud offshoots' (indicated by arrow). B) A typical internal tide deposit, collected from offshore Nigeria. 'Mud Couplets' (indicated by arrows) are thought to represent changing tides. Both core photographs taken from Shanmugam (2006).

Other bottom water sands that are receiving increasing interest in the literature are those deposited by internal wave and tides (Zhenzhong and Eriksson 1998; Shanmugam 2003; 2011; Youbin et al. 2008). Internal tides are usually observed within downslope canyons and feature many traction surfaces and other sedimentary features, most notably a characteristic 'mud couplet' is attributed to changing tidal directions (Fig. 7.9; 7.12 B).

Therefore, care should be taken when applying the facies models and conclusions of this study to other systems to ensure the correct model is applied. The study of contourites sands is a novel and rapidly expanding area of research and a collective effort at subdividing these different bottom current processes is yet to be achieved.

7.3 Conclusions

The Gulf of Cadiz contourite depositional system has illustrated the complexity of these systems and the varied deposits they contain. Chapter 6 outlines the modern day sand-dominated contourite system in the east and a Pliocene sandy contourite drift and mixed system in the north of the study area. It is clear from examining acoustic, facies and sedimentary data that there are many features of contourite sands that are comparable to those seen in other deposits (e.g. those of turbidites).

The positive identification of a sediment facies as contourite remains extremely challenging. Mud-dominated contourites are easily confused with pelagic and hemipelagic muds (Dall'Olio et al. 2010), whereas silty- and sandy-contourites may be confused with turbidites. Although rare, even gravel-lags from the bottom of high-energy contourite channels may look similar to those of a debris flow at sediment scale.

Much progress has been made in the understanding of differences between deposits using seismic data. Faugères et al. (1999) summarise the morphological differences between contourite drifts and turbidite levee systems. On a *facies* scale however, careful evidence must be gathered to distinguish between deep ocean processes, particularly where they are interbedded or hybrid beds exist. The turbidite facies models such as the Bouma Sequence show very characteristic features for the identification of turbulent, short-term flow over an area, characteristically with a normal grading trend. Contourite facies tend to show much more gradual transitions between grain sizes on account of a steady waxing then waning bottom water flow. The result is a bigradational sequence (Stow and Faugères 2008). Difficulties arise where partial sequences are present and it is important to assess the presence of bioturbation within associated finer-grained beds and identify reverse graining within the sequences. Here, a new set of facies models has been presented for fine-grained to coarse-grained contourites as each facies shows very different features (Fig. 7.9). The use of grain size parameters can be used as further evidence for distinguishing depositional environment, with characteristic ‘end member’ grain size distributions identified for differing processes (Fig. 7.10). However, care should be taken as such distributions are significantly modified where multiple processes are ongoing, and can also be affected by sediment provenance. Above all, a good understanding of the palaeoceanographic and tectonic set-up of the margin is important.

Interpretation & Discussion

Chapter 6: The Gulf of Cadiz sandy contourite depositional system

Chapter 7: Characterising contourite sands

Chapter 8: Contourite controls and sequence stratigraphy

Chapter 9: Contourite reservoir potential and economic importance

8 Contourite Controls and Deep Water Sequence Stratigraphy

This chapter marks a move away from analysis of solely data acquired over the course of this research thesis, and towards some more conceptual ideas using knowledge from the study of the Gulf of Cadiz along with the wider published literature. Contourites and contourite sands are found along many of the continental margins, and therefore some key conclusions cannot be made using the Gulf of Cadiz as an exclusive example. To evaluate the broader importance of contourite sands and the key controls of sand deposition and accumulation, examples from over twenty drifts across the world have been used. Below, the large-scale depositional controls of contourite sedimentation are discussed and a new sequence stratigraphic model proposed. The main aim of this model is to allow for future prediction of contourite sands in the subsurface, as will be discussed further in chapter 9. The below work is largely published in the Brackenridge et al. (2011) Geo-Marine Letters paper named '*Contourites within a deep-water sequence stratigraphic framework*' (Appendix 1).

One of the dominant paradigms for the description and interpretation of continental margin sedimentary systems is sequence stratigraphy, as developed from the seminal work of Peter Vail and others in the late 1970s. Sequence stratigraphy provides a dynamic view of stratigraphy which directly links variations in sea level and sedimentation, allowing a hierarchy of cycles of eustatic sea level changes to be recognised at a world-wide scale (Mitchum et al. 1977; Vail et al. 1977; Haq et al. 1987). Much progress has been made since that time and several different schools have emerged that promote rather different models. In their recent review of sequence stratigraphy, Catuneanu et al. (2009) state that "each model is justifiable *in the context in which it was proposed* and may provide the optimum approach under the right circumstances."

However, despite ever-growing interest in deep water sedimentation for hydrocarbon exploration, there is still no mention in any of these models of contourites and bottom currents. Even in Catuneanu et al. (2009), the discussion of deep water settings makes no reference to the alongslope system. This is despite the recognition of contourites as a possible seismic mounded facies in early work on seismic stratigraphy (Mitchum et al. 1977). Furthermore it is now clearly recognised that contourite deposits are a hugely important component of deep water depositional systems, everywhere from the upper continental slopes to the abyssal plains (e.g. Stow et al. (2002c); Viana and Rebesco (2007); Rebesco and

Camerlenghi (2008)). These deep water systems, especially along continental margins where many of the contourites are found, are currently frontier areas for hydrocarbon exploration and production (Stow and Mayall 2000; Haughton and Kendall 2009; Nielsen et al. 2011). The integration of contourite depositional systems (CDS) with downslope systems is of paramount importance in this context.

Whereas individual drifts have been previously evaluated in terms of sequence stratigraphy, e.g. Llave et al. (2011), and sea level has been considered as one of the important controls on contourite drift evolution, e.g. Faugères and Stow (2008), no generally applicable sequence stratigraphic model has yet been developed. The problem is indeed challenging because the interaction of additional controls is complex; there is an apparent disconnection between northern and southern hemisphere ocean circulation, and there is no simple relationship between alongslope and downslope systems. But, the time is well overdue and the database does now exist for this important first attempt to place contourite depositional systems firmly within a sequence stratigraphic framework by modifying the conventional downslope model. This chapter develops concepts introduced by Faugères et al. (1993; 1999), Diez et al. (2008) and Hernández-Molina et al. (2008). It is an additional challenge to refine the model by detailed analysis of industry-generated seismic data-sets that are age controlled with well calibrations.

The principal aims of this work, therefore, are: 1) To consider the range of controls that influence contourite drift development and bottom current erosion in deep water; 2) To consider specifically the role of sea level variation in this regard; and 3) To develop a new deep water model that places the contourite depositional system within a sequence stratigraphic framework.

8.1 Sequence Stratigraphy: Existing Models and Problems

Sequence stratigraphy can be defined as the analysis of genetically related depositional units within a chronostratigraphic framework (Mitchum et al. 1977). It grew out of the subsurface analysis of continental margins by oil explorationists using seismic profiling and deep borehole techniques, and has now become a fully-fledged sub-discipline of geology (Vail et al. 1977; Haq et al. 1987; Posamentier et al. 1988; Posamentier and Vail 1988; 1991; Van Wagoner et al. 1988; Emery and Myers 1996; Catuneanu 2006).

Individual units recognisable on seismic profiles are known as depositional sequences. These are bounded by distinctive unconformity surfaces (Type 1 or 2) and comprise an internal arrangement of sub-units (or systems tracts), which are associated to particular variations in sea level. One of the basic tenets of sequence stratigraphy is that sea level acts as a fundamental control on margin sedimentation by influencing the delicate balance between accommodation space and sediment influx (Myers and Milton 1996). Individual systems tracts result from the changing relationship between these two important controlling factors.

The most widely used sequence stratigraphic model is illustrated in Fig. 8.1. At the base, the sequence boundary represents a surface along which significant erosion and/or a hiatus in sedimentation occurred. This can result from a dramatic drop in eustatic sea level, causing the continental shelf to be exposed to sub-aerial erosion (Type 1 boundary) or not (Type 2 boundary). The subsequent lowstand systems tract (LST) is normally subdivided into three depositional units in deep water: the basin-floor fan, slope fan, and lowstand wedge. The basin-floor fan signifies bypass of sediment from the shelf downslope into the deep basin. Following, or simultaneous with basin floor-fan deposition, muddier turbidite and debrite downslope processes result in the formation of a slope fan. Slow relative sea level rise and restored slope stability is responsible for the development of an overlying prograding lowstand wedge, which develops into the transgressive wedge when the formation of accommodation space exceeds sediment deposition. Collectively, the lowstand elements present a retrogradational architecture. The overlying transgressive systems tract (TST) is bounded by the transgressive surface at its base and the maximum flooding surface along its upper limit (Posamentier et al. 1988; Posamentier and Vail 1988). This is then overlain by the highstand systems tract (HST) which represents deposition at a time of limited accommodation space resulting from the slowing of relative sea level rise. If sediment supply is sufficient then a progradational depositional architecture will be observed (Fig. 8.1).

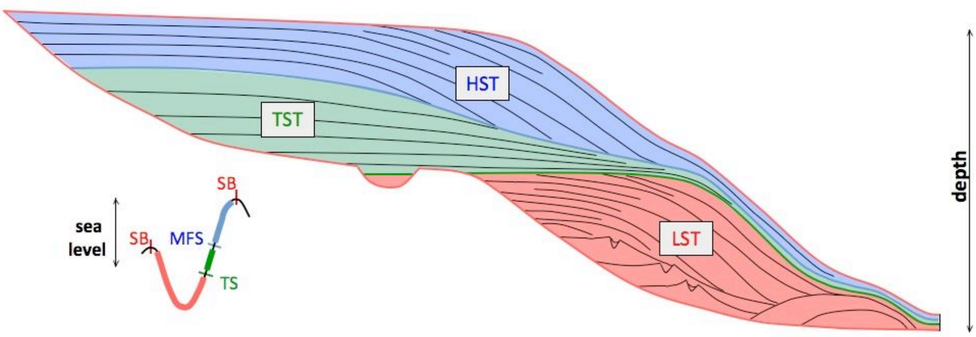


Figure 8.1 Basic sequence stratigraphic model for a continental margin sequence architecture where right is basinwards. The figure shows the 3-fold systems tracts model where LST=lowstand, TST=transgressive and HST=highstand. Important bounding surfaces are: SB=sequence boundary, TS=transgressive surface, MFS=maximum flooding surface. Important components of the LST are: basin-floor fan and slope fan. Most basin sedimentation occurs during the LST. Figure is schematic and not to scale but approximately 10s-100s km across and 100m–few km deep. Modified from Haq et al. (1988).

While this model reflects a simplified response to eustatic sea level variation and presents a schematic sedimentary architecture for siliciclastic systems, the reality on many continental margins is more complex (Posamentier and James 2009). Key issues include:

- Carbonate-dominated systems behave quite differently, as has been clearly demonstrated by numerous authors (Emery and Myers 1996; Schlager 2005; Catuneanu 2006). Mixed silici-bioclastic systems present a further challenge for interpretation.
- Synsedimentary tectonic activity can significantly affect accommodation space, sediment supply, or both. In some cases this can completely mask sea level effects (Bridge and Demico 2008). Therefore 'relative sea level' is a more accurate term to be used when discussing continental margin sedimentary architecture.
- The presence of ice along a margin can significantly alter the sedimentary architecture (Powell and Cooper 2002).
- In reality, the lowstand wedge and prograding highstand systems tract rarely downlap onto the deep water elements, as demonstrated by Haughton and Kendall (2009). Furthermore the so-called slope fan is not everywhere distinct from the basin-floor fan, but commonly represents its channel-levee feeder system.
- Many of the continental margins around the world have a slope-apron fringe of sediment and no distinct slope or basin-floor fan, a point long emphasised by various authors, e.g. Stow et al. (1996). In these cases, the lowstand systems tract, in particular, will be very different from that of the standard model (Shanmugam 2006).
- In the standard model, depositional sequences mostly reflect second- and third-order changes of sea level (i.e. 1-10 My duration), whereas systems tracts and parasequences reflect third- and fourth-order changes (100 ky to 1 My). The growth and development of large submarine fan systems may span two or more normal depositional sequences, while internal variation of sequences can occur with higher frequency (e.g. 10-100 ky) (Myers and Milton 1996).
- Pliocene and Quaternary sequence stratigraphy models are rather complex and present important differences to conceptual models. In contrast to idealised sequence stratigraphic models the existence of the regressive (forced or not) systems tracts (RST) is likely to predominate in the Pliocene and Quaternary sedimentary record (Hunt and Gawthorpe 2000).
- Finally, as stated previously, none of the existing models take into account the very significant and sometimes dominant elements of alongslope sedimentation – the contourite depositional systems. This is the primary focus of this chapter.

8.2 Controls on Deep Water Sedimentation

For the interpretation of any sedimentary system, including deep water systems, it is important to consider the full range of factors that have influenced the accumulation of sediment and its preservation. These comprise of both external and internal controls. The principal external controls include: 1) Sediment supply – the nature, rate and source of supply, as well as the type of sediment; 2) Sea level changes – eustatic and relative sea level fluctuations, as well as short-term tidal, seasonal and storm effects; and 3) Climate – temperature, precipitation and wind regimes, as well as short- and long-term climatic changes.

Internal controls can be equally significant in affecting sedimentation. These include: 1) Tectonic activity – isostatic movements, subsidence and uplift, plate tectonic setting, seismicity and volcanicity; 2) Local physical, biological and chemical processes – the nature and intensity of bottom currents, and the degree of interaction with other processes; 3) Post-depositional processes – compaction, deformation, biogenic and chemogenic effects, amongst others; and 4) Regional bathymetry – water depth, slope gradient and seafloor irregularity;. These ultimately influence the available accommodation space – controlling progradation and/or aggradation.

The rates and length of time over which the controlling processes operate is also of vital importance. For example, sediment supply, and hence accumulation rates, can be 2-3 orders of magnitude greater for deltas than contourite drifts. These various controls have been more extensively discussed by numerous authors (Walker and James 1992; Reading and Levell 1996; Allen 1997; Leeder 1999; Bridge and Demico 2008).

In order to simplify our understanding of this complex interplay of controls, conventional sequence stratigraphic models assume two primary controls; sediment supply and sea level variation. Myers and Milton (1996) have more recently expressed this as sediment supply and accommodation space (where accommodation space is a function of eustatic sea level, tectonics and compaction) as shown in Figure 8.2. The balance between accommodation space and sediment supply form the stratigraphic stacking patterns in the original downslope model (Fig. 8.1).

8.3 Controls on Contourites

Previous attempts to understand the controls on contourite development have clearly emphasised the numerous interlinked factors listed above (Faugères and Stow 1993; Viana et al. 1998; Faugères et al . 1999; Shannon et al. 2005; Diez et al. 2008). These can be resolved

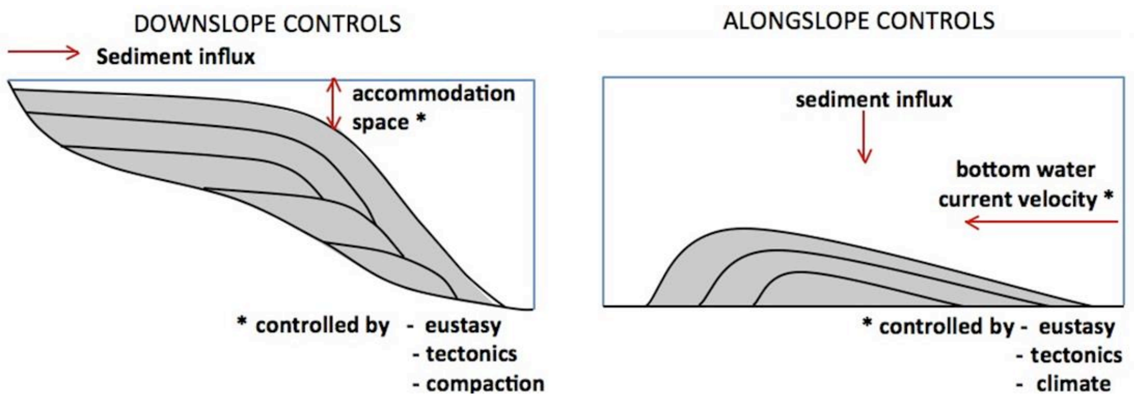


Figure 8.2: The controls on downslope vs. alongslope depositional systems.

into *two primary controls* for contourite sedimentation: bottom current intensity and its variation, and sediment supply (Fig. 8.2). Unlike for near-shore depositional systems, accommodation space is a less significant factor (except in the case of shallow water contourites). Sea level affects the system by influencing bottom current intensity and sediment supply, as discussed below.

8.3.1 Bottom Current Variations

It has long been realized that the nature of contourite deposition, both in the long- and short-term, is controlled primarily by the existence of and variation in bottom currents (Stow et al. 2008; 2009). Bottom current velocities control the facies and bedforms of a drift, in addition to determining areas of deposition and erosion on the sea bed. Drift development requires bottom currents to be stable and effective for a prolonged period of time. Mean current velocities must be maintained at > 0.1 ms^{-1} to allow for significant re-working, transportation and deposition of contourites, whereas non-deposition and seafloor erosion become more prevalent at velocities > 0.5 ms^{-1} (Stow et al. 2009). Long-term fluctuations in bottom currents lead to an apparent cyclicity of seismic facies from which palaeoceanographic information may be extracted.

The cause of these fluctuations is still a major topic of debate and ongoing research; however, general consensus would identify the very important effects of (a) oceanic gateways, and (b) prevailing conditions in the source areas (or kitchens) for bottom water generation. There is a considerable body of research that seeks to explain short-term (e.g. decadal) variation in ocean circulation, especially following the paper by Bryden et al. (2005) on the slowing of meridional overturning circulation in the North Atlantic linked to climate change. There is also a considerable body of palaeoceanographic literature on climate change and circulation patterns over the recent glacial-interglacial cycles (Rahmstorf 2002). However, to our knowledge there has been no attempt to directly link deep water circulation with sea level change (Bacon, pers. comm. 2010; Piola, pers. comm. 2011). The theoretical considerations presented below are therefore proposed as a new explanation of just how variations of sea level act to influence bottom water generation and current intensity. This is an important step in understanding the link between sea level and contourite development.

8.3.1.1 Gateway Effects

Oceanic gateways are critical to the exchange of both surface and deep water masses between ocean basins (Legg et al. 2009) (Fig. 8.3). They are therefore critical to the presence or absence and to the relative intensity of bottom currents associated with intermediate and deep water masses. At times of high sea level, there is a normal and full exchange of water masses through the gateway, and hence bottom currents will be strong and well developed. At intermediate sea level (during either transgressive or regressive phases), a gateway's cross sectional area will be reduced (Fig. 8.3), thus limiting bottom water exchange and intensifying the associated bottom currents by morphological forcing. It may be that upper, less dense strands of bottom currents are intensified, whereas lower, denser strands are diminished. During sea level lowstands, the bottom water mass becomes severely limited or completely shut off, such that bottom currents are also reduced in intensity or are non-existent. This model can be altered when water mass thicknesses are adjusted for different climatic conditions, for example a thinning of the surface waters during glacial lowstand conditions.

8.3.1.2 Bottom Water Kitchen Conditions

The global thermohaline circulation system is fed by the continued and abundant generation of cold saline bottom waters in specific cold-water kitchens at high latitudes, including the Norwegian-Greenland Sea, Labrador Sea, Bering Sea, Weddell Sea and other locations around Antarctica (Rahmstorf 2006). Empirical differences have been noted in the timing of generation between Northern and Southern Hemispheres, which has been referred to as the see-saw effect (Steig 2006). Additional intermediate waters are formed in marginal basins such as the Mediterranean Sea. This is thought to be more representative of bottom water generation during global greenhouse conditions (Gross and Gross 1996).

The *Northern Hemisphere* deep water kitchens in the Arctic regions show high rates of bottom water generation and accelerated overturning in the North Atlantic during interglacials and associated highstands (Rahmstorf 2002; Piotrowski et al. 2004; Lynch-Stieglitz et al. 2007; Knutz 2008). The following mechanism is here proposed. Cooling of surface waters is most effective where it occurs over broad shelf areas, both with and without floating ice shelves, at periods of relative high sea level, and the heat-exchange dynamics between atmosphere/ice

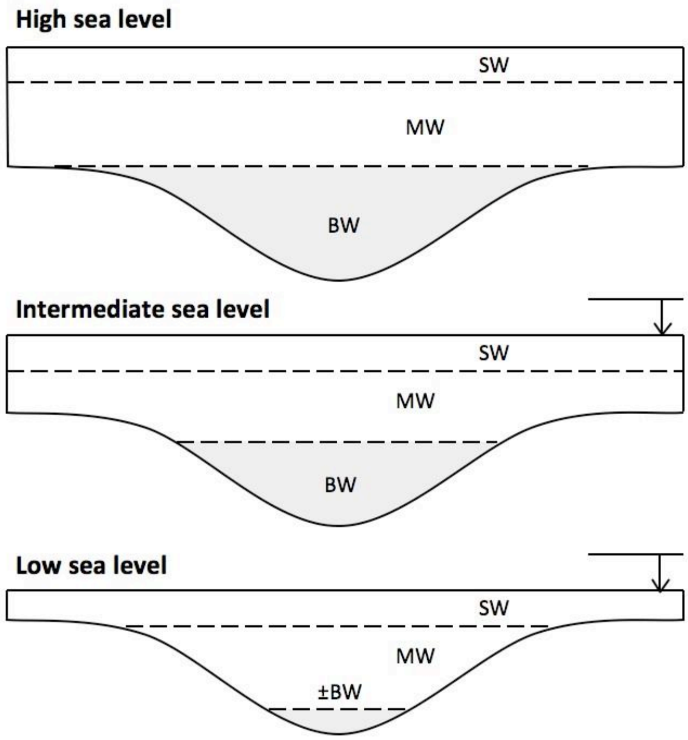


Figure 8.3: The effects of changing seal-level on the exchange of water masses through oceanic gateways. BW=bottom water; MW=middle water; SW=surface water.

shelf and ocean surface are particularly effective. The consequent active generation of cold dense water leads to vigorous overturn, off-shelf spillover and downslope flow of the dense bottom water (Fig. 8.4a). Where this reaches its density equilibrium, the cascading water mass turns alongslope under the influence of Coriolis Forces and proceeds away from the source area hugging the bottom contours. Slightly warmer waters are then drawn over the shelf to replace those lost to cold water generation, and the process continues.

At low relative sea level (Fig. 8.4b), the shelf (partially or wholly) becomes subaerially exposed and where an ice shelf had existed it becomes grounded. This results in a smaller or non-existent, shelf-centred cold-water kitchen area and hence a reduction in the most effective bottom water kitchen area. In other words, both the lack of shelf area and the grounding of ice on shelves prevent the influx of 'warmer' surface water to drive the overturn. Heat exchange still occurs between atmosphere and the open ocean surface but is less dynamic across the main body of the open ocean. Although large areas of the open ocean may become covered in floating sea ice, generation and sinking of denser water is relatively diffuse and the bottom water does not become focussed along a continental margin. The overall result is a slowing of cold dense water generation, and less vigorous thermohaline overturn. This leads to more sluggish bottom currents and circulation. In reality, the system is not necessarily as simple as the model suggests. For example, the generation of Arctic Intermediate Water may show an increase during cold-climate lowstands due to brine injection. There are also expected changes and interruptions to meridional overturning caused by short-term climatic events (Llave et al. 2006; Rogerson et al. 2012).

For the *Southern Hemisphere* there is even less unequivocal evidence for the link between climate/sea level and bottom water generation and the whole process appears very complex with brine injection playing an additional important role. There is certainly evidence of an expanded influence of Antarctic Bottom Water into the Atlantic during glacial times and lowered sea level, but less direct evidence for increased bottom current velocity (McCave et al.

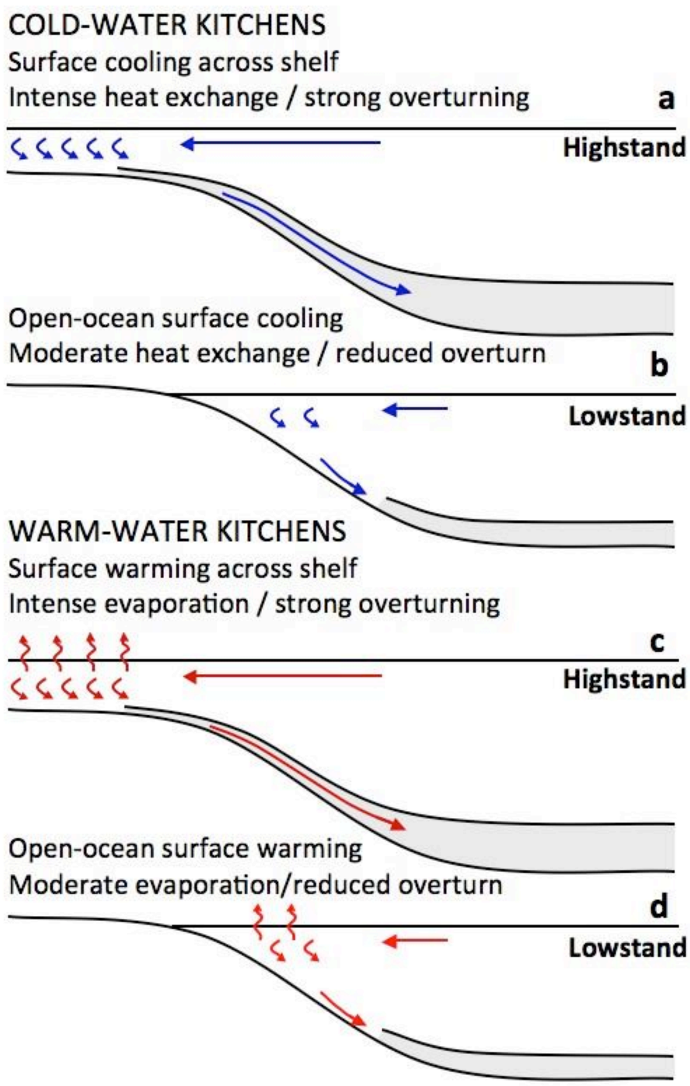


Figure 8.4: The effect of sea level on the generation of bottom water. A. High-latitude cold water kitchens, sea level highstand. B. High-latitude cold water kitchens, sea level lowstand. C. Low-latitude warm water kitchens, sea level highstand. D. Low-latitude warm water kitchens, sea level lowstand.

1995; Orsi et al. 1999; Schmittner 2003; EPICA Community Members 2006; Negre et al. 2010). It is quite possible that this expanded influence is largely the result of the infilling of the 'accommodation space' left by reduced generation of Northern Hemisphere deep waters. There is better evidence for an accelerated Antarctic Circumpolar Current at depth during glacial periods, but as this is largely driven by surface wind shear it cannot necessarily be correlated with increased bottom water generation in cold-water kitchen areas.

Furthermore, during times of extensive sea-ice development, all water circulation is pushed basinwards, and therefore the core location for bottom water generation is likewise shifted. This is particularly visible in the water masses surrounding Antarctica where the Antarctic Circumpolar Current moves northward at times of sea-ice development (Rebesco et al. 1997). This may push the bottom currents away from the continental slope where morphological forcing was likely to have caused accelerated bottom current velocities. On the other hand, at least part of the extremely deep shelf areas around Antarctica still maintained floating ice shelves during glacial lowstands and hence the same effective method of bottom water generation as highstands. With colder water and a greater level of freezing to form sea ice, there is potential for increased bottom water generation during glacial periods. This would support the inferences of higher bottom current velocities being linked to colder climates for the Southwest Pacific Gateway (Goosse et al. 2001; Carter et al. 2004), and along the Argentine margin (Hernández-Molina et al. 2009; 2010).

(c) Warm-water kitchen effects (Fig. 8.4 c; d). The principal warm-water kitchen for intermediate/deep saline water today is found in the Mediterranean Sea. This ultimately gives rise to the Mediterranean Overflow Water (MOW), which escapes through the Gibraltar Gateway into the North Atlantic Ocean. During previous Greenhouse conditions on the planet, such warm-water kitchens of the geological past would have been still more important than today and, at times (such as much of the Cretaceous period, for example), they would have provided the dominant source of bottom water (Gross and Gross 1996).

At high relative sea level stands, broad shallow shelf areas, in arid and semi-arid climatic zones, provide the most effective regions for heat exchange, leading to the rapid evaporation of surface waters, increased salinity and hence density of the sea water left behind, and its consequent sinking and downslope flow to form intermediate and bottom water masses (Fig. 8.4c). Coriolis force deflects the newly generated water mass to flow alongslope as a dense but warm-water bottom current. Cooler surface waters flow across the shelf region to replace that lost to warm-water generation.

At low relative sea level stands (Fig. 8.4d) the shelf may become subaerially exposed and unable to provide such a large warm-water kitchen area. Heat exchange still occurs between atmosphere and the ocean surface but evaporation is less efficient across the main body of the open ocean, warm saline and dense water is generated more slowly and/or more diffusely and there is less vigorous overturning.

Whereas this proposed model can be applied in general for warm-water kitchens and higher sea levels during global greenhouse conditions in the geological past such as was seen during the Cretaceous when humid conditions prevailed, there remains some controversy in the literature with regard to Plio-Quaternary variations for the Mediterranean and Red Sea warm-water kitchens which are located in arid zones. According to Rohling and Zachariasse (1999), the Red Sea Outflow was severely reduced during the last glacial maximum (and lowered sea level). However, for the Mediterranean, Cacho et al. (2000) see evidence for enhanced overturning rates during the last lowstand, while several authors working in the Gulf of Cadiz see a denser increased bottom current flow of the lower strand of the MOW (Hernández-Molina et al. 2006; Schmiedl et al. 2010; Toucanne et al. 2007; Voelker et al. 2006). The upper strand, by contrast, appears to have higher velocities during warm-water highstands (Stow et al. 2002b). This bottom water generation mechanism is therefore highly sensitive to local climatic conditions that control run off and hence bottom water mass salinity.

8.3.2 Sediment Supply Variations

The second fundamental control on contourite development is sediment supply. For contourite accumulation to occur, sediment supply must be greater than background pelagic and hemipelagic fall out. Stow et al. (2008) identified the potential contourite sediment influx sourced from turbidity currents, pro-delta plumes, slope spillover, hemipelagic and pelagic settling from both upstream and directly at the drift site. Additionally, erosive bottom currents are capable of reworking previously deposited sediments.

The influence of sea level on these different sediment sources is not easy to ascertain and is not everywhere the same. As recognised in conventional sequence stratigraphic models for siliciclastic systems, deep water clastic sedimentary systems are enhanced during sea level fall and lowstand periods (RST and LST) on account of an increase in clastic sediment influx to the deeper basins. This is due to enhanced erosion of the shelf, direct sediment supply to the shelf-edge/upper slope, increased activity of downslope processes and increased sediment bypass of the slope. Although more material is therefore likely to be available for redistribution by bottom currents, contourite depositional systems may become masked by the dominance of downslope systems (Faugères et al. 1999; Fulthorpe et al. 2010).

On the other hand, during times of high relative sea level, clastic sediment is more likely to become trapped on the shelf until the accommodation space has reduced sufficiently to allow for progradation to the shelf edge. However, large rivers will still feed pro-delta plumes across the shelf, especially in the case of narrow shelves, and contribute to some degree of hemipelagic sedimentation. Off-shelf sediment spillover processes will become more prevalent as more mobile sediment is fed to and reworked across the shelf (Viana et al. 1998; Stow et al. 2002a). It should be noted that sediment supply to the deep ocean basins is by no means driven solely by eustatic sea level fluctuation. Climate and local tectonics are additional concerns.

8.4 Sequence Stratigraphy of Drifts: Case Studies

Here, 20 contourite drifts for which good data exists have been investigated, either using literature and/or from first-hand studies. Published industry data with good well control through contourite systems is very rare, partly because the alongslope component has either not been recognised or is too shallow in the section to be of economic interest. However, an extensive published database includes over 150 scientific drill sites (DSDP, ODP, IODP) that have penetrated contourite or bottom current systems and published seismic profiles from over 30 separate drifts and CDS (Faugères and Stow 2008). From a survey of this database, information for 20 well-documented drift systems has been compiled in Table 8.1. They cover a wide range of environments including those from high and low latitudes, northern and southern hemispheres and different tectonic settings. Of these, four examples have been selected as case studies; the CDS off the Antarctic Peninsula in the SE Pacific Ocean, the Argentine Basin CDS in the south-western Atlantic, the Eirik Drift in the Northern Atlantic and the Gulf of Cadiz CDS (Fig. 8.5). They have been chosen to enable a direct comparison of Northern and Southern Hemisphere systems in addition to cold water vs. warm water systems.

DRIFT	WATER MASS(ES)	TIME OF MOST VIGOROUS BW VELOCITY	TIME OF HIGHEST SEDIMENT INFLUX	TIME OF GREATEST CONTOURITE SEDIMENT ACCUMULATION	*MODEL*
ANTARCTIC PENINSULA DRIFTS	AABW; ACCBW	Glacial lowstand	Glacial lowstand	Late Miocene **LOWSTAND**	*2*
ARGENTINE BASIN ELONGATE MOUNDED	AABW	Glacial lowstand	Glacial lowstand	Late Oligocene-Early Miocene **LOWSTAND**	*2*
BALKE BAHAMA OUTER RIDGE	NADW	Interglacial highstand	Glacial lowstand	Pliocene **TRANSGRESSION** and **HIGHSTAND**	*1*
BARRA FAN DRIFT	NADW; LDW	Interglacial highstand	Glacial lowstand	Holocene **TRANSGRESSION** and **HIGHSTAND**	*1*
CANTERBURY BASIN DRIFTS	SC	Glacial lowstand	Glacial lowstand*	Mid-Late Miocene **LOWSTAND**	*2*
CEUTA DRIFT	MU	Glacial lowstand	Glacial lowstand	Quaternary **LOWSTAND**	*2*
CHATHAM TERRACE DRIFT	AABW	Glacial lowstand	Glacial lowstand	Masked by local tectonic activity	*2*
COSMONAUT SEA MARGIN DRIFTS	AABW	Glacial lowstand	Glacial lowstand	Mid-Late Miocene **LOWSTAND**	*2*
EIRIK DRIFT	NADW	Interglacial highstand	Glacial lowstand	Pliocene **TRANSGRESSION** and **HIGHSTAND**	*1*
FARO-ALBUFEIRA DRIFT	MOW	Glacial lowstand	Glacial lowstand	Plio-Pleistocene **LOWSTAND**s	*2*
FENI DRIFT	NSOW; LDW	Glacial lowstand	Glacial lowstand	Mid- Late Pleistocene **LOWSTAND**	*2*
HATTON DRIFT	NADW	Interglacial highstand	Glacial lowstand	Plio-Quaternary **TRANSGRESSION** and **REGRESSION**s	*1*
LOFOTEN DRIFT	AIW	Interglacial highstand	Glacial lowstand	Quaternary **LOWSTAND**s	*n/a*
NE ROCKALL TROUGH DRIFT	NADW; NSOW;	Interglacial highstand	Glacial lowstand	Unknown	*1*

	LDW				
NYK DRIFT	AIW	Interglacial highstand	Glacial lowstand	Quaternary **HIGHSTAND**s	*1*
UPPER SLOPE CAMPOS BASIN DRIFTS	BC	Interglacial highstand	Glacial lowstand	Present **HIGHSTAND**	*1*
VEMA CONTOURITE FAN	AABW	Glacial lowstand	Glacial lowstand	**TRANSGRESSIVE** and **HIGHSTAND****	*n/a*
VESTERÅLEN DRIFT	AIW	Interglacial highstand	Glacial lowstand	Quaternary **LOWSTAND**s	*n/a*
WEST SHETLAND DRIFTS	ISOW	Interglacial highstand	Glacial lowstand	Neo-Quaternary **TRANSGRESSION** and **HIGHSTAND**s	*1*
WILKES LAND DRIFTS	AABW	Glacial lowstand	Glacial lowstand	Neo-Quaternary **LOWSTAND**s	*2*

*Table 8.1: Summary of drifts used to create a revised sequence stratigraphy model that incorporates alongslope deposits. AABW=Antarctic Bottom Water; ACCBW= Antarctic Circumpolar Bottom Water; AIW=Antarctic Intermediate Water; BC= Brazil Current; ISOW= Iceland-Shetland Overflow Water; LDW=Lower Deep Water; MOW= Mediterranean Overflow Water; MU= Mediterranean Undercurrent; NADW= North Atlantic Deep Water; NSOW= Norwegian Sea Overflow Water; WBC= Western Boundary Current; * AND low relative sea level resulting from uplift. Local uplift has now resulted in the downslope sediment 'drowning' (covering) this contourite system; **Doesn't fit with model due to unusually high erosion of contourite sediments occurring during lowstand. Information compiled from: Stow and Holbrook (1984); Robinson and McCave (1994); Laberg et al. (2001); Ercilla et al. (2002); Escutia et al. (2002); Faugères et al. (2002a); Howe et al. (2002); Rebesco et al. (2002); Stow et al. (2002a); Viana et al. (2002); Van Weering et al. (2008); Carter et al. (2004); Laberg and Vorren (2004); Hernández-Molina et al. (2006); Hohbein and Cartwright (2006); Llave et al. (2007a); Diez et al. (2008); Hunter (2007); Fulthorpe et al. (2010); Hernández-Molina et al. (2010).*

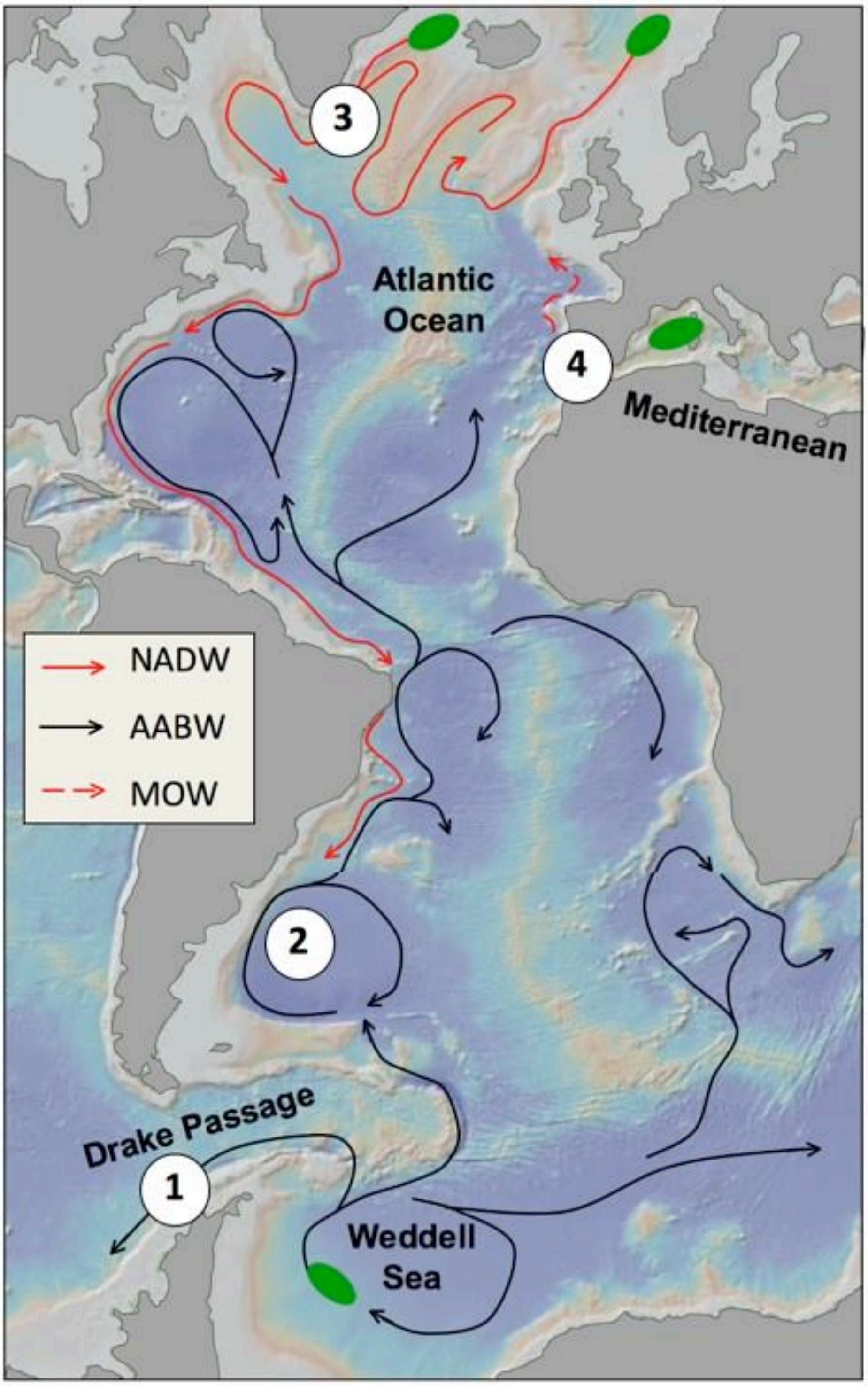


Figure 8.5: Principal bottom water circulation trends (arrows) around the Atlantic continental margins. Bottom water source kitchens are highlighted in green: the low-latitude cold-kitchens in the Arctic and Weddell seas and the warm water kitchen in the Mediterranean. Main water masses are North Atlantic deep water (NADW); Antarctic bottom water (AABW); and Mediterranean overflow water (MOW). Numbered contourite drifts are those referred to in the text; 1) Antarctic Peninsula drifts; 2) Argentine Basin drifts; 3) Eirik Drift; 4) Gulf of Cadiz drifts (Modified from McCave and Tucholke 1986; Faugères et al. 1992).

8.4.1 Antarctic Peninsula drifts

8.4.1.1 Location and Setting

Twelve drifts have been identified on the continental rise off the Antarctic Peninsula, in the SE Pacific Ocean. They have been deposited by a boundary current that flows southwestward from the Weddell Sea region, via the Drake Passage (Fig. 8.5). This current flows counter to the eastward flowing Antarctic Circumpolar Current. As a result, the evolution of these drifts is closely related to the palaeoceanography of the Antarctic region and the opening of the Drake Passage. The most thoroughly researched one of these, Drift 7 (Rebesco et al. 1997; 2002; Van Weering et al. 2008), is documented here (Fig. 8.6).

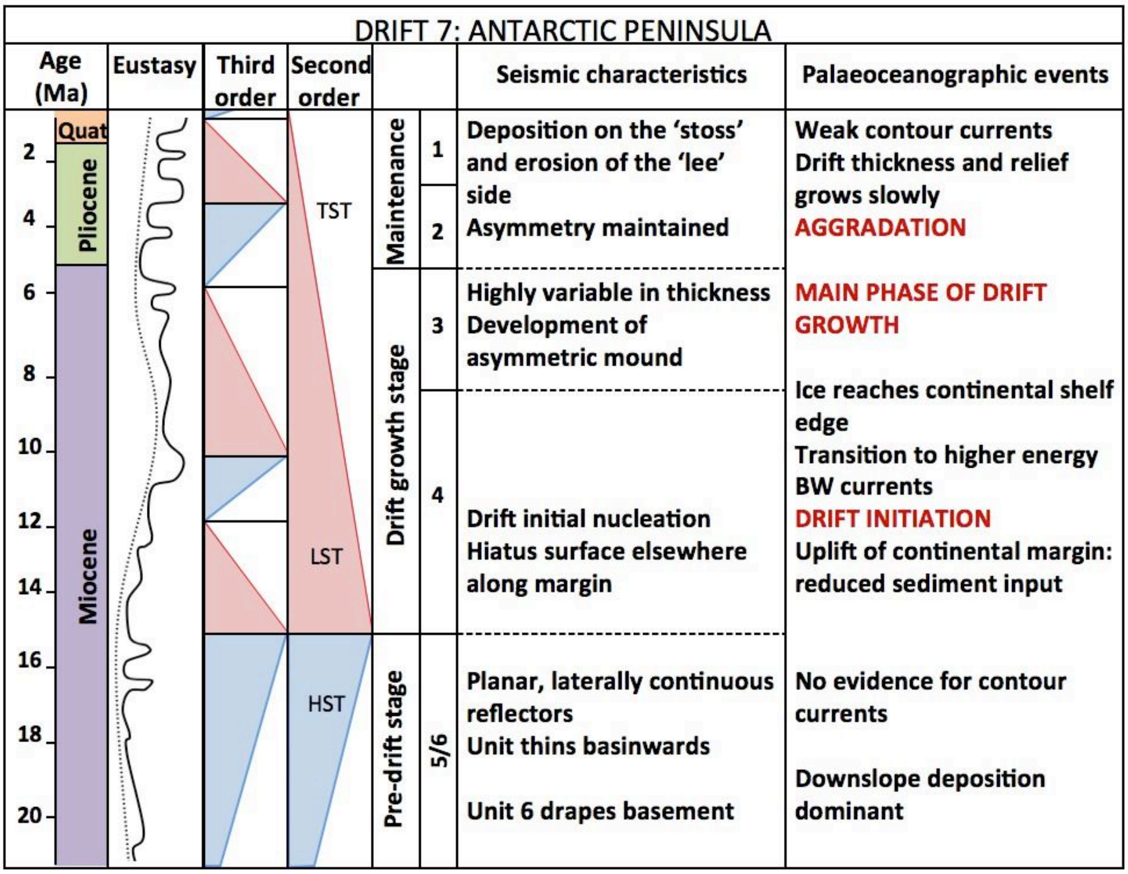


Figure 8.6: Paleoceanographic events and seismic characteristics associated with the evolution of Drift 7, Antarctic Peninsula. The main phase of drift building coincides with rising relative sea level. It should be noted that the local tectonic evolution of the margin is the dominant control over relative sea level and glacial activity is an additional important control to consider along this margin. Quat. = Quaternary. Adapted from Haq et al. (1987); Rebesco et al. (2002); Hunter (2008); Ogg and Ogg (2008).

8.4.1.2 Evolution and Controls

Pre-drift sediments are mainly turbiditic, aged between 36 and 15 Ma B.P., and cover the oceanic basement. Drift growth began at ca. 15 Ma B.P. (Fig. 8.6) when bottom current velocities increased sufficiently to dominate over downslope processes. This has been linked to continued deepening of the Drake Passage and the drop in sea level following the mid-Miocene climatic optimum and the subsequent expansion of the East Antarctic Ice Sheet. Climatic changes continued to affect the drift throughout its evolution, as the Antarctic ice sheets extended seawards and glacio-eustatic levels fluctuated. 'Drift Growth' and 'Drift Maintenance' stages have been identified (Fig. 8.6). Drift growth is accounted to combined high bottom current velocities and high sediment influx during glacial conditions and associated eustatic lowstands, there is some change in drift accumulation rates during the Plio-Pleistocene and this succession is named the 'Drift Maintenance Stage' (Fig. 8.6). This was probably related to the onset of permanent ice in the Arctic and the increased importance of bipolar deep water generation mechanisms. At present there is little bottom current activity over the area.

8.4.1.3 Sequence Stratigraphy

This high latitude CDS is under a strong glacial control that has four main effects on the drift. First, numerous authors have noted an increased rate in Antarctic Bottom Water (AABW) formation during times of glacial advance due to increased brine injection (EPICA Community Members 2006; Rahmstorf 2006). Second, sediment supply to the basin is greatly increased during times of glacial advance. Third, it has been hypothesized that the Antarctic Circumpolar Currents are pushed northward during glacial times (Rebesco et al. 1997), and therefore there is less interaction between the bottom currents and the drifts. Finally, glacial advance across the continental shelf alters the sediment input to the margin significantly, with enhanced contourite sedimentation rates being observed at times of sea level lowstand. The bottom waters along this margin rarely reach velocities capable of eroding sediment. When observations on seismic records and evidence on shorter timescales using core data are considered with respect to drift evolution off the Antarctic Peninsula, it is seen that glacial periods are preferential to drift growth due to higher velocity bottom water currents and increased sediment supply that can be pirated by enhanced flow.

8.4.2 Argentine Basin Drifts

8.4.2.1 Location and Setting

A complex CDS has been described from the continental margin offshore Argentina (Hernández-Molina et al. 2009; 2010; Violante et al. 2010). Alongslope activity in the basin initiated close to the Eocene-Oligocene boundary (Fig. 8.7) and has been attributed to the opening of the Drake Passage. The Argentine Basin has since been affected by the deep Antarctic water masses. From the Middle Miocene onward, the development of thermohaline circulation in the Northern Hemisphere has facilitated the additional influence of the NADW on this contourite depositional system. Water masses enter the Argentine Basin via deep narrow passageways in the topographic highs that enclose it. The water masses are then pushed against the continental margin due to the Coriolis Forces to form an intensified boundary current. Along the upper continental slope, plastered drifts developed and a mounded drift has formed on the lower continental slope under the influence of complex basin circulation pathways.

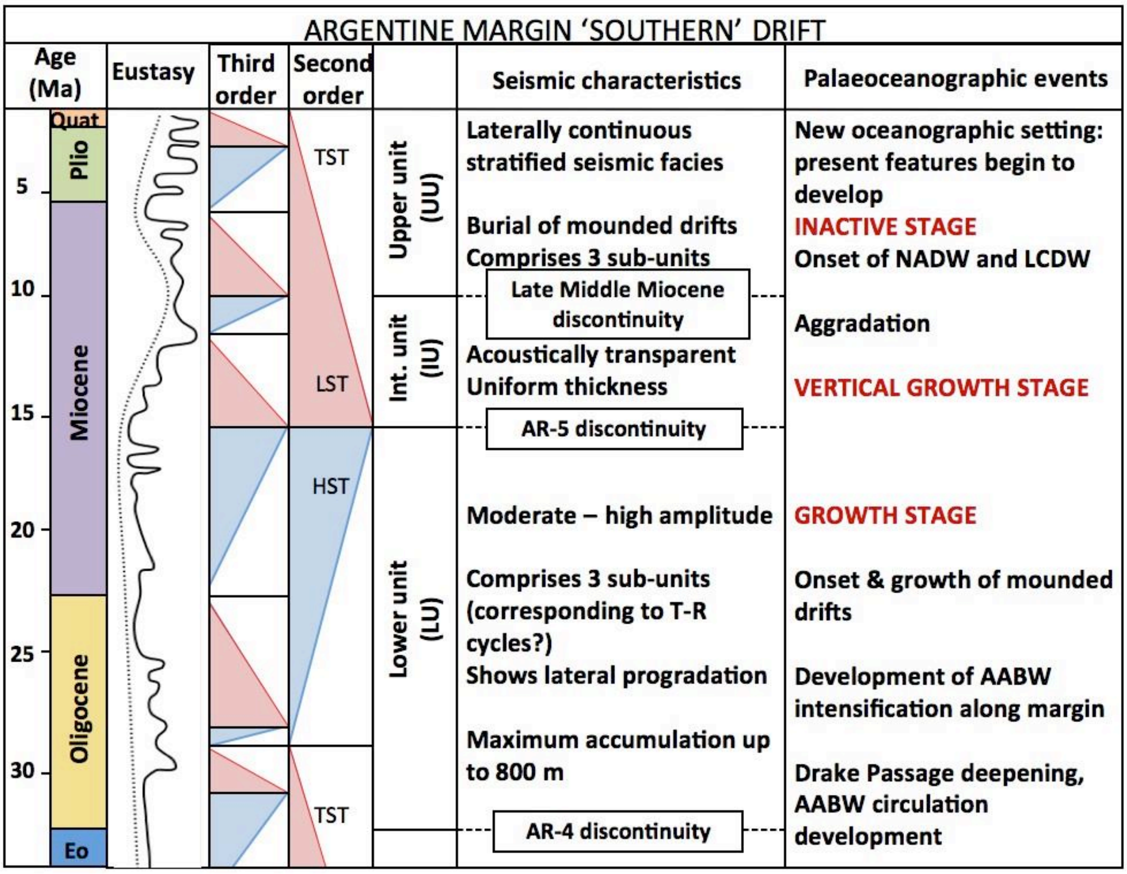


Figure 8.7: Paleoceanographic events and seismic characteristics associated with the evolution of the Southern Drift, Argentine Basin. After contour current initiation in the Early Miocene, drift growth was rapid. Despite a global lowstand in the Middle-Late Miocene, localised deepening of the Drake Passage allowed drift growth to continue, illustrating the importance of gateways on CDS evolution. Quat. = Quaternary; Plio. = Pliocene; Eo. = Eocene. Adapted from Haq et al. (1987); Hunter (2008); Ogg and Ogg (2008); Hernández-Molina et al.(2010).

8.4.2.2 Evolution and Controls

This CDS is made up of distinct erosional and depositional features developed in response to tectonic gateway openings and bottom current variations as influenced by climatic and eustatic changes. Three major depositional units (Fig. 8.7) have been identified on seismic records. Contourite activity in the basin commences with an erosional surface relating to the onset of AABW at approximately 33 Ma B.P. (Hinz et al. 1999). This occurred due to a number of interrelated factors; the deepening of the Drake Passage and the extension of the East Antarctic ice sheet and associated cooling that triggered the thermohaline circulation system in the Southern Hemisphere (Goosse et al. 2001; Carter et al. 2004). The subsequent sediment accumulation forms the lower seismic unit (LU) and signifies a phase of major drift growth. Bottom current velocities throughout the LU are thought to have fluctuated in response to the changing cross-sectional area of the Drake Passage. The main phase of drift growth occurred during a major global transgressive event, or sea level rise. A second major erosional discontinuity is thought to be related to the Middle Miocene lowering of eustatic sea level. This is followed by low accumulation rates and aggradational stacking patterns in the intermediate seismic unit (IU) associated with a third-order highstand (Ogg and Ogg 2008; Hernández-Molina et al. 2009). The final major seismic unit, the upper unit, is developed under the present day oceanographic configuration of the basin. Three sub-units have been recognised in the LU and three in the UU which may have formed in response to third-order T-R cycles (Fig. 8.7).

8.4.2.3 Sequence Stratigraphy

Although seismic is the main source of data in this region, some conclusions may be drawn on the sequence stratigraphy of the Argentine Basin CDS. Bottom current velocities appear to be more rapid at times of glacio-eustatic lows and this may lead to erosion, although sediment influx will be high. The Argentine margin therefore provides an example of a CDS under the influence of a bottom water current that is accelerated during glacial times and global eustatic lowstands. The evidence presented above shows that contourite erosion is likely to occur during lowstands, and sediment accumulation preferentially occurs during the lowstand to transgressive phases of systems tract development.

8.4.3 The Eirik Drift

8.4.3.1 Location and Setting

The Eirik Drift is a large Cenozoic elongated mounded drift located off the southern tip of the Greenland continental margin (Hunter et al. 2007; Hunter 2008). It is one of a number of contourite drifts formed in the Northern Atlantic Ocean that are closely linked to gateways and overflow waters from the Nordic and Arctic seas (Fig. 8.5). Located at depths up to 3,400m, it is elongated in a NE-SW orientation in response to the oceanographic set-up of the Greenland margin. Here, several deep water masses overspill from the Arctic Basin through gaps in the Greenland-Iceland Ridge and combine to form the Deep Water Boundary Current (Hunter 2008).

8.4.3.2 Evolution and Controls

The palaeoceanographic events of the Eirik drift are summarized in Fig. 8.8. There is evidence for bottom currents in the region from the Middle Miocene, when the relative sea level over the Greenland-Iceland Ridge reached sufficiently high levels to allow the exchange of water masses between the Atlantic and Arctic Oceans. At this time, bottom water formation in the Northern Hemisphere was vigorous and contourite sediment accumulation increased as more deep water was able to escape into the North Atlantic. Through the Late Miocene and Early Pliocene the bottom water circulation increased in intensity, as is evident from the formation

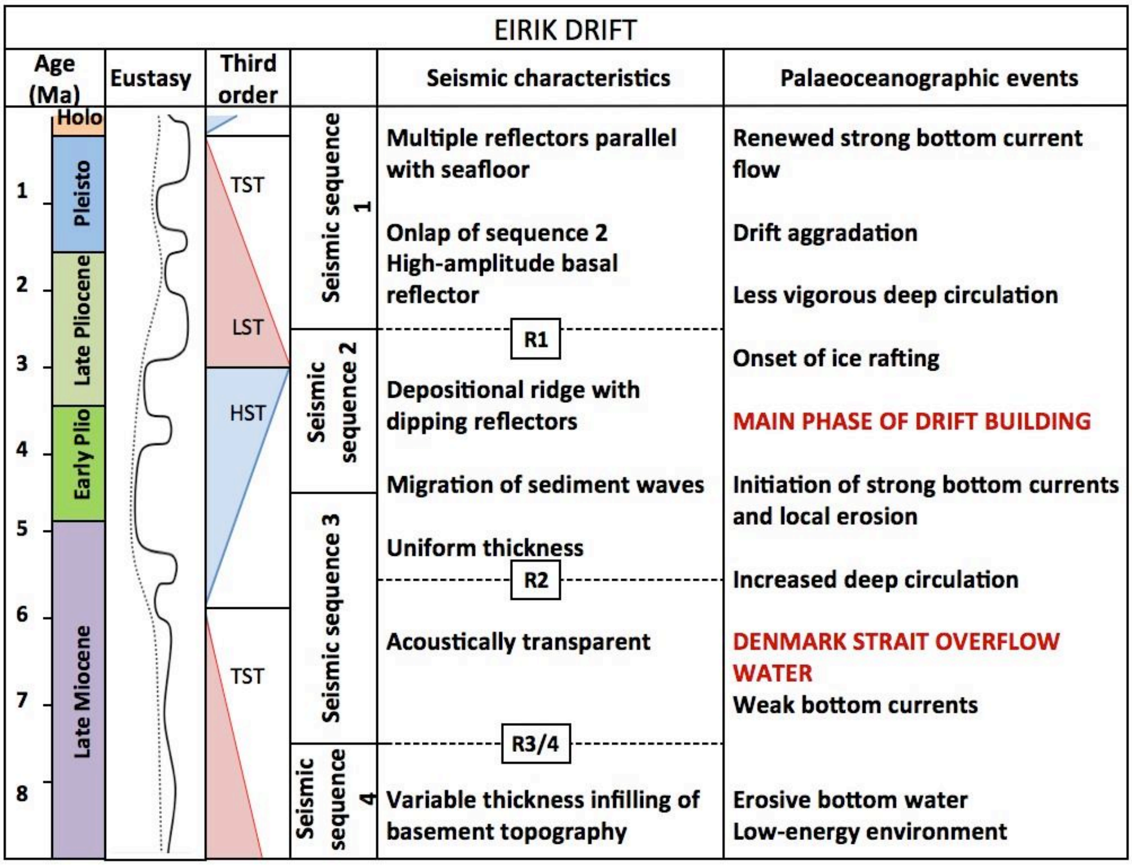


Figure 8.8: Paleoceanographic events and seismic characteristics associated with the evolution of the Eirik Drift, North Atlantic Ocean. The main phase of drift building coincides with highstand conditions. The Late Pliocene lowstand leads to slower deep water circulation in the region. Holo. = Holocene; Pleisto. = Pleistocene; Plio. = Pliocene. Adapted from Haq et al. (1987); Hunter (2008); Ogg and Ogg (2008).

of migrating sediment waves, drift progradation and localized erosion (Diez et al. 2008). Late Pliocene global sea level fall and ice sheet advance in response to cooling is coincident with a weakening of the bottom water current in the Eirik Drift region between 3 and 0.9 Ma B.P. (Knutz 2008), marked by a reduction in drift progradation and slowing in the rate of accumulation. The Holocene has seen evidence of renewed intensification of the Deep Water Boundary Current, coincident with increased rates of bottom water formation during times of global eustatic highs.

8.4.3.3 Sequence Stratigraphy

The sequence stratigraphic response of the Eirik Drift is in concurrence with observations in many other northern hemisphere contourite depositional systems influenced by deep Arctic water masses (Howe 1995; Stoker et al. 1998; Weaver et al. 2000; Gröger et al. 2003; Ovrebo et al. 2006). During the warm interglacials (sea level highstands and transgressions), strong bottom currents prevailed, leading to erosive surfaces, active bedform growth and CDS development. During lowstands, high downslope sediment influx can dominate and current velocities are seen to wane.

8.4.4 The Gulf of Cadiz CDS

8.4.4.1 Location and Setting

The Gulf of Cadiz CDS has developed over the past 4-5 My in response to the acceleration of the Mediterranean Outflow Water (MOW) through the Gibraltar Gateway (Hernández-Molina et al. 2003; 2006; Llave et al. 2007c). The MOW generates an intermediate mid-slope bottom current comprising relatively warm but saline water produced in the warm-water kitchen of the eastern Mediterranean Sea (Fig. 8.5). In this respect it is thought to resemble palaeoceanographic conditions during the extremely high sea levels and warm greenhouse conditions of the Middle and Late Cretaceous period. Diapiric ridges orientated perpendicular to MOW flow (Tasianas 2010), form morphologic obstructions and create distinct channels through which the water mass splits into two pathways; the Mediterranean Upper and Lower Waters. As a consequence, a complex drift system has developed along the northern margin of the Gulf of Cadiz including both erosional and depositional domains and numerous different drift types (Hernández-Molina et al. 2006).

8.4.4.2 Evolution and Controls

Drift initiation occurred when the Gibraltar Gateway opened and deepened sufficiently to allow significant MOW to escape into the Atlantic. This occurred during the Early Pliocene, ca.4 Ma B.P. (Fig. 8.9). Contourite drifts such as the Faro-Albufeira drift are seen to be highly cyclical in nature comprising numerous seismic sequences and sub-sequences (Llave et al. 2001; 2006; Stow et al. 2002b). These are interpreted as being due to major long-term fluctuations in bottom current intensity (and settling depth), controlled by climatic-eustatic fluctuations or tectonic adjustments at the Gibraltar Gateway. There appears to be a basinward shift in the MOW during times of lowstand due to increased MOW density and lowered sea level as described in chapter 6. Several authors have demonstrated higher velocities of the lower branch of the MOW during glacial times (Cacho et al. 2000; Hernández-Molina et al. 2006; Llave et al. 2006; Toucanne et al. 2007) and an increased velocity of the upper branch of the MOW during the recent highstand period (Stow et al. 2002b; Hernández-Molina et al. 2014). Other key observations that relate to sequence stratigraphy are: increased sedimentation rates on drifts in the upper core of the MOW and a change from progradational to aggradational stacking patterns in response to rising sea level. Nelson et al. (1993) proposed a direct link between drift accumulation and relative sea level due to the changing cross-sectional area of the Gibraltar Gateway, although other factors such as fluctuating density of the MOW and tectonic activity have also played an important role in the development of the CDS during each evolutionary stage (Llave et al. 2007a).

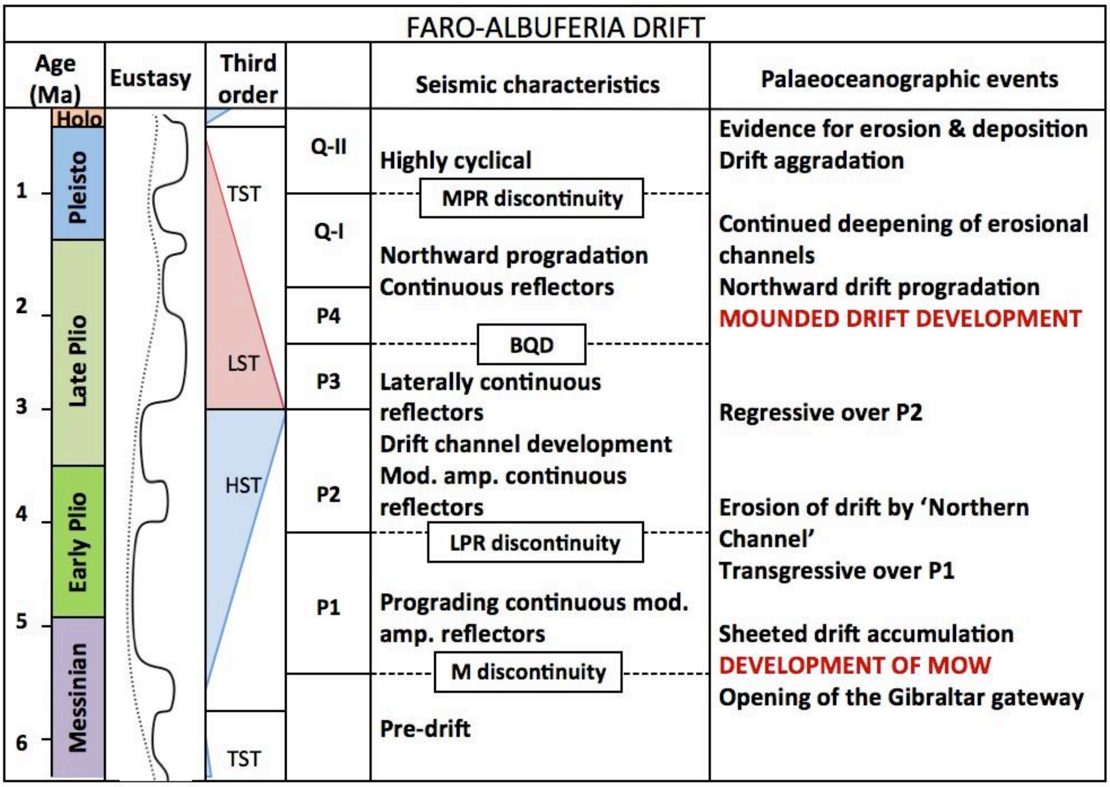


Figure 8.9: Paleoceanographic events and seismic characteristics associated with the evolution of the Faro-Albuferia Drift region in the Gulf of Cadiz. Holo. = Holocene; Pleisto. = Pleistocene; Plio. = Pliocene. Adapted from Haq et al. (1987); Nelson et al. (1993); Stow et al. (2002b); Llave, et al. (2007c); Hunter (2008); Ogg and Ogg (2008).

8.4.4.3 Sequence Stratigraphy

Different regions of the Gulf of Cadiz CDS appear to respond differently to eustatic changes. This is most likely due to the complexity of the region and the additional morphological and tectonic control along the margin. The available evidence indicates that greatest contourite accumulation occurs during times of glacio-eustatic lowstand when sediment is directly supplied to the slope and a vigorous deep and dense MOW sweeps the margin.

8.5 New Sequence Stratigraphic Model

This section attempts to combine the more theoretical considerations of controls on deep water sedimentation, including the influence of sea level variation on bottom currents and sediment supply, with the observational data gained from a detailed study of contourite depositional systems, especially those documented in Table 8.1 and in the four case studies presented above. This data shows that eustatic sea level changes affect bottom current generation and intensity differently, which is especially evident between the two hemispheres. It is therefore necessary to propose *two* new sequence stratigraphic models of shelf-slope-basin sedimentation that focus on contourite elements developed on alongslope-dominated margins (Fig. 8.10). Ultimately, determining into which category any given margin falls into will require a good understanding of the palaeoceanographic set-up of the region and a good ability to distinguish turbiditic and contouritic sediments at a seismc scale.

8.5.1 Model 1: Enhanced Bottom Water Currents during HST

Sequence boundary and LST: As with the conventional downslope slug diagram, the new model containing contourite deposits begins at the base with a sequence boundary, which is overlain by the lowstand systems tract (LST) (Fig. 8.10 a). During low relative sea level, the continental shelf may be subjected to subaerial erosion and the slope generally experiences sediment bypass. As a result, there is enhanced sediment deposition in the deep ocean basins and a basin floor and slope apron fan typically develop (Fig. 8.10 a). This increase in downslope sediment volume will affect contourite drift development by masking alongslope processes regardless of the bottom current velocity. Furthermore, the marked reduction in bottom current activity and velocity at times of low relative sea level provides conditions unfavourable for contourite development. However, at least on some margins there is evidence for muddy contourite deposits leading to the accumulation of thin, fine-grained sheeted drifts. In other cases these are commonly interbedded with more dominant turbidite and debrite sediment, leading to the formation of mixed contourite drifts as seen off the eastern U.S. and the Argentine continental margins (Faugères and Stow 2008; Huppertz, pers. comm. 2010).

TST: During the transgressive systems tract (TST), the influence of downslope processes wanes and there is renewed activation of bottom current generation and contourite deposition. This is typically expressed in the reworking of downslope sediment and the formation of elongate mounded drifts along the slope apron showing active alongslope progradation and/or aggradation (Fig. 8.10a). Sediment supply over the shelf edge is moderate and much of it fine-grained, greatly favouring muddy mounded drift development. Erosional unconformities are also common throughout the succession because minor fluctuations in bottom current velocity lead to repeated cycles of erosion and deposition.

This last point reveals an important departure from the existing models. Using conventional sequence stratigraphy laws (Van Wagoner et al. 1988) any erosional unconformity is tied to subaerial erosion and therefore requires a sea level *fall*. However, our model shows that regionally extensive unconformities can be associated with increased bottom current velocities and sea level *rise*. This is amply supported by observational as well as theoretical data (e.g., Shannon et al. (2005) for the NW UK continental margin).

HST: The gradation between transgressive and highstand systems tracts is indistinct with respect to contourite development and depends on the oceanographic setting of the margin in question. However, a trend of increasing bottom water generation in response to sea level rise will see more active bottom currents throughout the TST, climaxing in the HST. Downslope processes become muted so that bottom current activity is uninterrupted and better preserved. Elongate, mounded contourite drifts continue to accumulate, showing both alongslope progradational and aggradational patterns. Assuming that the maximum bottom current velocities reached are sufficiently high, contourite facies will have larger mean grain sizes so that sandy contourites will be more widely dispersed, generally as sandy sheeted drifts (Fig. 8.10 a). Under still stronger currents, non-deposition surfaces and erosional features become significant, including channels, gullies, furrows, moats and other less regular scour features. These too may be the focus of sandy contourite deposition.

Sediment supply to the bottom currents that construct contourite drifts will be variable during the HST, depending partly on geographic location of the margin and partly on other additional controls – especially tectonics and climate. During development of the prograding highstand wedge in the conventional model, sediment supply to the slope will increase and there is thus potential for enhanced sediment supply to any drift system active at this stage.

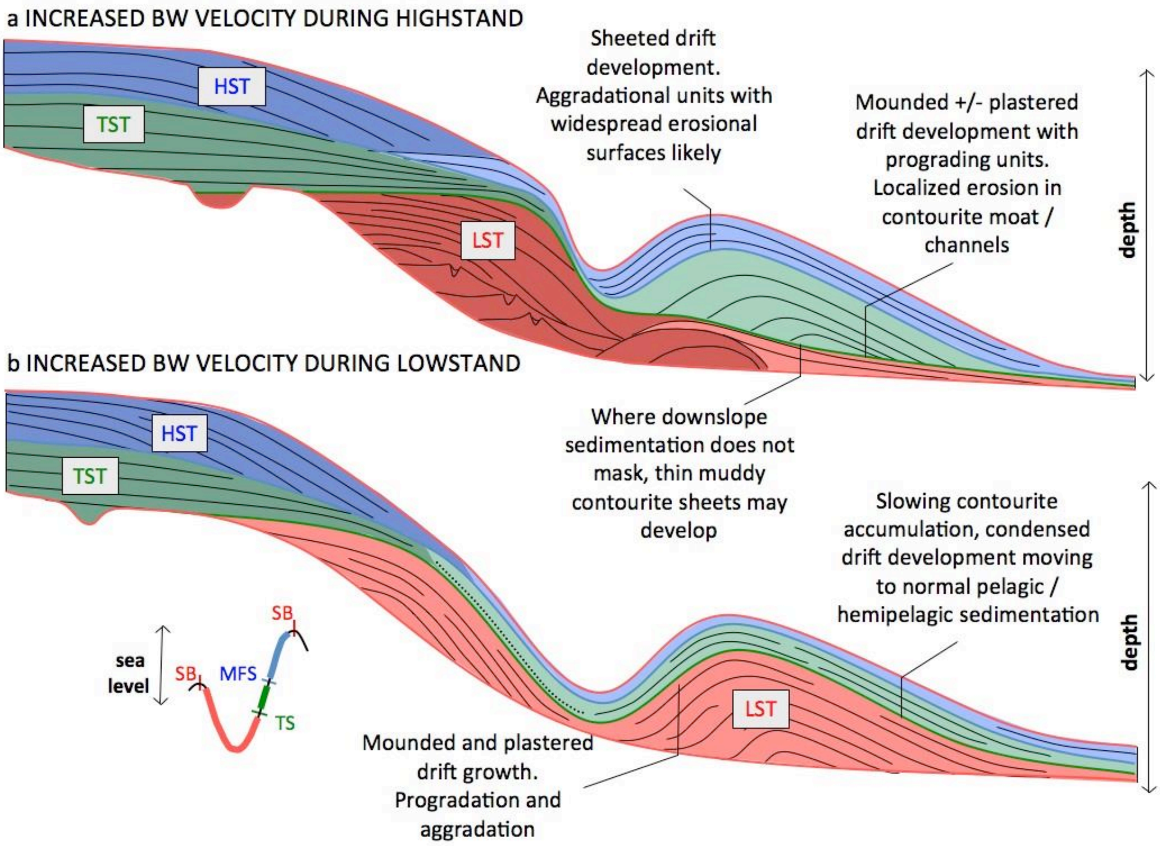


Figure 8.10: Revised deep water sequence stratigraphic models. a Model applicable along margins where bottom water circulation is more vigorous during times of highstand. b Model applicable along margins where bottom water circulation is more vigorous during times of lowstand. Darker colours represent downslope and lighter ones alongslope deposits. LST=lowstand, TST=transgressive and HST=highstand. Important bounding surfaces: SB=sequence boundary, TS=transgressive surface, MFS=maximum flooding surface. Figure is not to scale but approximately 10s-100s km in the horizontal and 100 m–few km in sediment thickness. Modified from an original model by Haq et al. (1988).

8.5.2 Model 2: Enhanced Bottom Water Currents during LST

Sequence boundary and LST: As with the previous model, low sea level triggers enhanced erosion of the shelf and terrigenous sediment bypass across the slope into the oceanic basins. Wherever bottom current velocities peak during times of sea level lowstand, the pirating of downslope sediments by bottom currents can result in the domination of contourite systems over the normally expected downslope LST sequence (Fig. 8.10 b). The result is high drift growth rates along the slope apron; some margins show accumulation rates that are an order of magnitude higher during LST where enhanced bottom currents redistribute large sediment influxes associated with glacial margins (Laberg et al. 2001; Rebesco et al. 2002).

Erosional processes by bottom currents may also be prevalent along continental margins at the times when bottom waters reach sufficient velocities. This is particularly common in regions where gateways may constrict and therefore further amplify bottom water velocities (Hernández-Molina et al. 2009), or where specific morphological forcing accelerates the flow (Viana et al. 2002). Expected sediment facies include sandy contourites where the maximum bottom current velocities are sufficiently high to transport larger mean grain sizes. Where erosional features become significant, channels, moats and terraces are likely to develop as is seen in the eastern Gulf of Cadiz. These too may be the focus of sandy and, in exceptional cases, also gravel-lag contourite deposition. Where bottom current velocities are insufficient for complete contourite domination of the margin, bottom current reworked sands (BCRS) may form where downslope sediments are modified and/or redistributed by bottom currents (Shanmugam 2012b).

TST: During transgressive systems tract (TST) development, downslope processes become more limited to the continental shelf and alongslope current cores begin to shoal. This is a transitional time for the system, during which accumulation rates slow down. Aggradational units are most likely and sheeted drifts thus prevail (Fig. 8.10 b). Bottom currents begin to slow down and therefore smaller average grain sizes are expected, although highly cyclical deposits will accumulate and ice rafted debris may be found in drifts deposited at higher latitudes. As with the model proposed for enhanced bottom currents during HST, erosional unconformities are common throughout the succession. These are formed in response to fluctuating bottom current velocities over the duration of deglaciation.

HST: Where high eustatic sea level is associated with relatively low rates of bottom water formation, contourite development is severely limited in the HST (Fig. 8.10 b). At such times, downslope sediment supply to ocean basins is low as sediment is trapped on the continental shelves. The combination of low bottom current velocities and limited sediment supply results in little to no contourite drift development and hemipelagic and pelagic sedimentation may become the dominant process along the continental slopes. Some degree of contourite drift deposition may occur where current speed is adequate for reworking of sediments supplied by slope spillover or normal pelagic settling (Stow et al. 2008).

As with model 1 HST, certain circumstances such as tectonic or climatic changes allow for downslope sediment progradation across the continental shelf and into the pathway of alongslope currents. If water velocities are insufficient to redistribute sediment entering the basin then downslope processes may prevail.

8.6 Discussion

The stratigraphy of contourite drifts has been used extensively to identify major global palaeoceanographic events. This chapter attempts to link these observations, together with theoretical considerations of sea level and other controls on bottom current variation, to sequence stratigraphic concepts by revising the original downslope model. This has been met with a number of challenges.

The original sequence stratigraphy model for downslope processes provided the definitions of systems tract boundaries. That is to say that the changing balances between sediment supply and accommodation space determine the systems tracts. For example, the maximum flooding surface (separating the transgressive and highstand systems tracts) is the point over which there is a shift from sediment supply being unable to fill the accommodation space to sediment supply exceeding the available accommodation space. Since accommodation space is not a *primary* control on deep water sediments, this distinction between systems tracts cannot be strictly valid for contourite depositional systems where a more gradual change between systems tracts is observed. Hence the contourite systems tracts identified in our model may not exactly match the downslope systems tracts of the conventional model.

A further consideration in placing alongslope processes into the existing sequence stratigraphic model is related to the orientation of system evolution. Downslope processes develop from the continent basinwards. Conversely, contourite depositional systems, evolve *parallel* to the continental margin and therefore along a different axis from downslope systems. This should be carefully considered when applying the models to an existing continental margin since a depositional sequence found at a location where downslope processes dominate (i.e. at a turbiditic fan) will differ from a continental margin adjacent to a turbidite fan. This is particularly important when examining contourites and bottom current reworked sands down current of turbiditic processes where pirating of sediment plays an important role.

It should be noted that the new models (Fig. 8.10) are in fact, idealised conceptual end-member models, and in reality there will be complications when applying the model to any existing geological system. In reality, any margin may be influenced by multiple bottom currents at different water depths simultaneously, or the margin morphology may force alternative stacking patterns (for example where contourite terraces are found as is seen in the eastern Gulf of Cadiz and the Argentine margins). The application of the end-member models here is exactly the same as for any existing sequence stratigraphic model and, as a consequence, many of the same problems arise when considering the sequence stratigraphy of downslope and alongslope systems. These problems have been discussed earlier in this paper. The considerations that are most significant to alongslope sequence stratigraphy are elaborated upon below.

(1) Synsedimentary tectonic activity can significantly affect sedimentary architecture along continental margins, in some cases completely masking sea level effects (Bridge and Demico 2008). Local tectonic adjustments will affect both downslope and alongslope systems similarly. Added complications to contourite systems arise from the extremely important role that tectonics play in CDS placement and development, since oceanic circulation is controlled by gateways. All the case study examples of contourite depositional systems presented in this chapter illustrate the intimate relationship between contourite drift development and ocean gateway openings. Perhaps the creation of gateways is the primary control on oceanic circulation on a first or second order timescale.

(2) The presence of ice along a margin can significantly alter the sedimentary architecture, sediment influx to a basin, rate of bottom water generation, or all of the above (Goosse et al. 2001; Powell and Cooper 2002; Van Weering et al. 2008). High latitude systems can therefore be difficult to predict and a model and may not always fit into the end-member model as seen in small-scale glacio-climatic fluctuations along the Antarctic Peninsula (Rebesco et al. 1997) and along the NW European margin (Laberg and Vorren 2004; Laberg et al. 2005).

(3) In the standard model, depositional sequences mostly reflect second and third order changes of sea level (i.e. 1-10 My duration), while systems tracts and parasequences reflect third- and fourth-order changes (100 ky to 1 My). The same will be true for alongslope systems; however, as with deep water turbidite fans, drift systems are capable of spanning two or more normal depositional sequences. This is clearly evident along the Canterbury Basin drifts which continue to grow through numerous downslope system sequence boundaries (Fulthorpe et al. 2010).

(4) The movement of water masses across a continental margin can be significantly affected by climatic and eustatic fluctuations. Changing density contracts affect water mass settling depths and these can be highly mobile over time and space. Bottom currents may, therefore, affect completely different parts of the continental margin at HST, TST and LST.

(5) The mechanisms for bottom water mass generation are highly variable and controlled not only by sea level but also climatic conditions, sediment influx etc. The Cretaceous bottom water circulation remains poorly understood.

(6) Seabed physiography plays an important role in modifying the expected response of bottom currents. Erosional contourite terraces will modify the model significantly, and features such as channels locally amplify bottom currents in an otherwise sluggish regime.

8.7 Conclusions

Where applied with care and a good understanding of a system, the models presented here can greatly facilitate the interpretation of margins that include or are dominated by contourites. External controls, in addition to sea level, should always be carefully considered with respect to how they might affect the contourite depositional system because models will never be applicable everywhere. Sequence stratigraphy has proven to be a highly valuable tool in hydrocarbon exploration of downslope sedimentary systems and it is therefore highly likely that a sequence stratigraphic model for contourite systems could prove to be a strong predictive tool.

A next step in this line of research is to assess how robust the model is in other settings and drift types: for example, in shallow water or abyssal plain contourite systems. Work by Viana et al. (2002) has begun to address this topic in the Campos Basin shallow water contourites. Here, sea level lowstand events are associated with distinctive current waning and increased downslope facies deposition. Subsequent sea level rise lead to the deposition of sandy facies with bedforms and increasing erosion. This suggests that the sequence stratigraphy model put forward in this paper can also be applied to shallow water contourites in addition to the deep sea contourite systems for which it was developed. Future work should specifically focus on the collection of datable material in order to provide better time constraints for the assessment of the sequence stratigraphic evolution of a given drift at numerous time scales.

Interpretation & Discussion

Chapter 6: The Gulf of Cadiz sandy contourite depositional system

Chapter 7: Characterising contourite sands

Chapter 8: Contourite controls and sequence stratigraphy

Chapter 9: Contourite reservoir potential and economic importance

9 Contourite Reservoir Potential & Economic Importance.

One of the key aims of this PhD research is to assess the link between contourites and the petroleum industry with a specific focus on the reservoir potential of contourite sands. Bottom currents are most vigorous along the continental margins and sweep the majority of the petroleum basins in the Atlantic Ocean at velocities of 0.1 cm s^{-1} to 3 m s^{-1} (Fig. 9.1). They are therefore of concern to petroleum explorationists due to 1) bottom current related hazards and 2) their reservoir potential upon burial.

Site surveying is essential prior to drilling and laying infrastructure in order to assess the risks these bottom currents pose. Appendix 7 outlines some of the problems site survey companies face, and some ways in which contourite science can aid the de-risking of an installation site. The key water current-related risks identified include: 1) triggering mass transport processes; 2) pipe-line walking and fatigue; and 3) additional stress to risers and tethers.

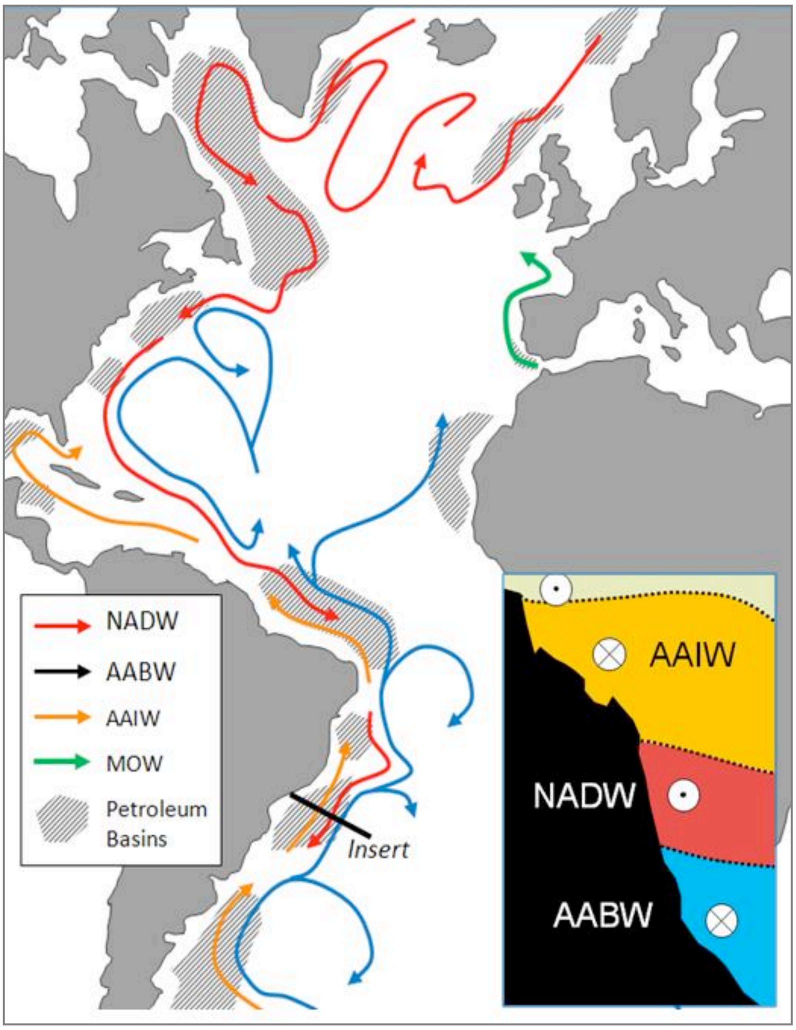


Figure 9.1. The major deep-water hydrocarbon provinces and frontier regions (blue shaded) and the dominant bottom water masses that sweep these regions. NADW= North Atlantic Deep Water; AABW= Antarctic Bottom Water; AAIW= Antarctic Intermediate Water; MOW= MOW. Modified from Faugères and Stow (1993); Viana et al. (1998); Stow and Mayall (2000).

Here, primarily the reservoir potential of contourite sediments is considered. The modern contourite sands in the Gulf of Cadiz have shown clean (up to 95% sand) contourite accumulations showing that contourite drifts do have the potential to make good hydrocarbon reservoirs. If sandy contourite sediments are to be exploited for economic reasons in the future, reservoir characterisation is essential since misinterpretation will effect reservoir architecture prediction and properties for reservoir simulation. To date, they have only been positively identified and produced offshore Brazil (Mutti et al. 1980) on account of the problems in positively identifying them in the subsurface (Viana et al. 2007). Other potential reservoir facies show increasing evidence for contouritic origin. Cretaceous chalks in NW Europe show signs of contourite deposition in places (Surlyk and Lykke-Andersen 2007) and some oil shales in North America are hypothesized to be the result of bottom currents (Viana and Almeida Jr. 2012).

9.1 The Reservoir Potential of Contourites

There is growing interest from the petroleum industry for an increased understanding of contourites and their reservoir potential. Recent publications and conference presentations (Moraes et al. 2007; Viana et al. 2007; Stow et al. 2011; Mutti and Carminatti 2012; Brackenridge et al. 2013b) have increased the exposure of these deposits to industry. This, along with ever-improving data coverage and quality along the deep water continental margins has resulted in more contourites being identified in the subsurface. Sadly, there is a long way to go before these are de-risked as potential exploration targets, but as modern-day analogues such as the Gulf of Cadiz CDS are characterised, and more subsurface examples are identified, our understanding of these systems and their reservoir potential is increased. Other potential contourite reservoirs are also being considered such as calcicontourites (Hüneke and Stow 2008; Surlyk and Lykke-Andersen 2007), gas hydrate (Shao et al. 2007) and oil shale (Viana and Almeida Jr. 2012) deposits.

Here, we clarify the definitions of contourite *sands* that are in the literature, and discuss their reservoir potential using the Gulf of Cadiz as an analogue with other examples from literature. Other sand-rich contourite facies are identified offshore Brazil (Viana et al. 1998), northeastern UK (Akhmetzhanov et al. 2007), the South China Sea (Gong et al. 2012) and in the Gulf of Mexico (Shanmugam 2012b). Alternative reservoir facies will also be touched upon. For any hydrocarbon play to successfully work the system must contain four essential elements: 1) a mature source rock; 2) a reservoir rock; 3) a seal and 4) some required thickness overburden rock. Additional processes that must occur are trap formation and the generation, migration and accumulation of hydrocarbons (Magoon and Beaumont 2003). These aspects of petroleum systems will also be discussed with contourites in mind.

9.1.1 Controls on Sand Deposition

For a significant contourite sand accumulation to form, certain conditions must be maintained for a prolonged period of time. Key controls identified for contourite sand accumulation are: 1) Sediment availability, 2) Current intensity, and 3) Seabed physiography (Viana et al. 1998).

1) *Sediment availability*; Perhaps the most key control on sand deposition in deep ocean basins is the availability of sediment. The continental slope, rise and abyssal plain are dominated by muddy sediment, and a sandy source is required for any reservoir facies to accumulate. In the case of the Gulf of Cadiz, shelf spillover plays an important role in the system, with sand spilling off the shelf close to the Gibraltar Gateway and being entrained into the MOW. It can then be transported alongslope for many hundreds of kilometres before being deposited. There is likely another, more minor alongslope current erosion component also. Another important sediment source in many sandy contourite depositional systems is derived from downslope processes. In the north of the Gulf of Cadiz, Pliocene downslope sediments are thought to have been pirated by the MOW and deposited in an adjacent, alongslope orientated contourite sheeted drift. Other examples of this process are seen offshore Brazil (Mutti et al. 1980). Where bottom currents are insufficiently vigorous to pirate and deposit coarse sediment, they may rework turbidite deposits to form bottom current reworked sands as is seen in the Gulf of Mexico (Shanmugam et al. 1995) or cause downslope channel migration as is seen in the South China Sea (Gong et al. 2012). Finally, Viana (2008) suggests that erosion and exposure of sandy sediments on the sea bed by tectonic movements may also provide a sediment supply.
2) *Current intensity*; For contourite sands to be deposited, vigorous bottom current velocities are required. Viana et al. (2007) quote that velocities of >30 ± 10 cm s^{-1} are required for sand wave formation, although muddy sands may start forming at much lower velocities. Not only are strong bottom currents required, but they are required to be persistent over geological timescales for any significant thickness to accumulate (Fig. 9.2 A). This is particularly important in high energy environments where erosion is common and accumulation rates are reduced. It is therefore unlikely that short-lived oceanic events, for example internal tides and tsunamis, will result in significant sand thicknesses. The frequency of variability of bottom current velocity will also affect the accumulation. Wind-driven currents, for example, are highly variable in nature and velocity due to the changing atmospheric conditions. Thermohaline-driven currents are

more persistent over geological time, albeit with a climatic and tectonic control. As a result, they tend to form the largest contourite deposits along continental margins (Fig. 9.2 B).

3) *Seabed physiography*: For bottom currents to erode, transport and deposit sand, some mechanism for current acceleration is required. Sand deposition requires bottom current velocities in the order of 0.5 – 1.5 ms^{-1} (Stow et al. 2009) (Fig. 9.2 B). Deep ocean circulation is much more commonly found as a broad sluggish flow of around 0.1-0.3 ms^{-1}. Much like when you place your thumb across the opening of a water hose to intensify the jet, so too it is necessary to have some morphological forcing to constrict the bottom current into a core and therefore cause its acceleration (Viana et al. 2007). Such features may be oceanic gateways, diapiric ridges, tectonic highs, or steep continental slopes in addition to contourite depositional feature-associated channels or moats. The Gulf of Cadiz shows us that with sufficient morphological forcing, sand can be transported great distances by alongslope currents (>200 km in this case).

Fulfilment of these controls can occur in a number of depositional environments influenced by bottom currents, the most common of which are: 1) Sand-rich contourite depositional systems, where bottom water deposition and erosion *completely* dominate over any other process along the margin, and 2) Bottom current reworked sands which are effectively mixed systems consisting of downslope-supplied sediment that is significantly winnowed and modified by bottom currents to result in sand accumulation. Additional bottom currents can also deposit sands, for example internal waves, internal tides and tsunamis, but these are

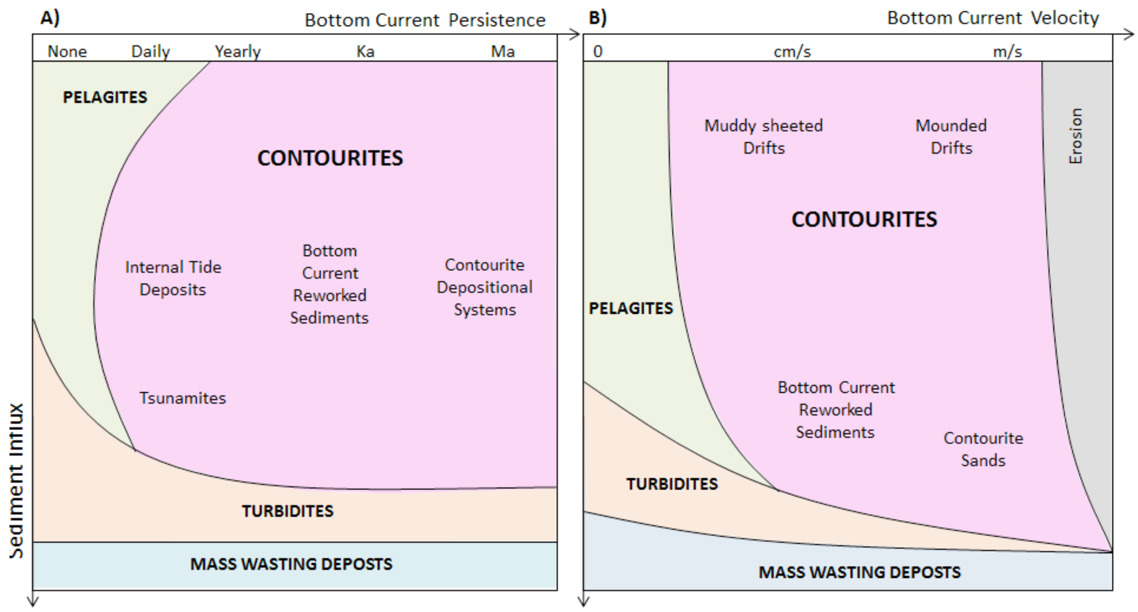


Figure 9.2: A) Sediment influx vs. bottom current persistence and the types of expected deposits. B) Sediment influx vs. bottom current velocity.

more poorly understood and appear to form much thinner accumulations of minimal reservoir potential.

There is a great degree of confusion in the literature as to the true definition and distinction of sediments deposited by bottom currents. Adding to the generally accepted definition of contourites (Stow et al. 2002c; Rebesco 2005; Rebesco and Camerlenghi 2008), it can be said that *contourite sands are sediments deposited by or significantly affected by bottom currents*. In reality, such deposits require high energy bottom currents and therefore tend to have erosional features associated with them. It is therefore perhaps more appropriate to term them *sand-rich contourite depositional systems*.

9.1.2 Contourite Sand Products

There are a number of contourite depositional environments that favour sand deposition that broadly proximal to distal trend as: 1) Sand and gravel channel bed deposits within erosional contourite channels; 2) Sheeted drift sands consisting of small-scale erosional features (furrows) and sandy bedforms (sand ribbons, dunes); and 3) Discrete beds within contourite mounded, plastered or fan drifts (Fig. 9.3). Where downslope processes are interacting with contourite deposition, bottom current reworked sands may also accumulate (Fig. 9.3). A successful reservoir must provide good reservoir properties to be economically viable for production. Main concerns are reservoir geometry, reservoir distribution/stacking and internal reservoir characteristics – the porosity (ϕ) and both vertical and horizontal permeability (k_v and k_h). Care will be taken to discuss each of these for all the possible contourite reservoirs below.

9.1.2.1 Sand Deposits within Erosional Contourite Channels

Undoubtedly the coarsest and most commonly found sands within contourite depositional systems are those deposited within channels. Contourite erosional channels can be formed by external forcing (structural highs or diapiric ridges) or through self-forcing (e.g. contourite moats) (Fig. 9.3). Examples have been found in the North Atlantic (Akhmetzhanov et al. 2007), offshore Brazil (Viana et al. 2007) and in the study presented here in the Gulf of Cadiz (Stow et al. 2013b). Of all the possible contourite sands, this facies is the most likely to retain some primary bedding structures, with laminations and cross bedding preservation in rare examples (Table 9.1). High bottom current velocities in contourite channels will lead to gravel lags, clean coarse sands, and erosional surfaces and hiatuses (Stow et al. 2009) due to winnowing by vigorous bottom currents. In the Gulf of Cadiz, these sands reach > 90 % sand content with high net-to-gross and show moderate to poor sorting. Away from the channel axis, there is a marked reduction in contourite sand thickness and quality.

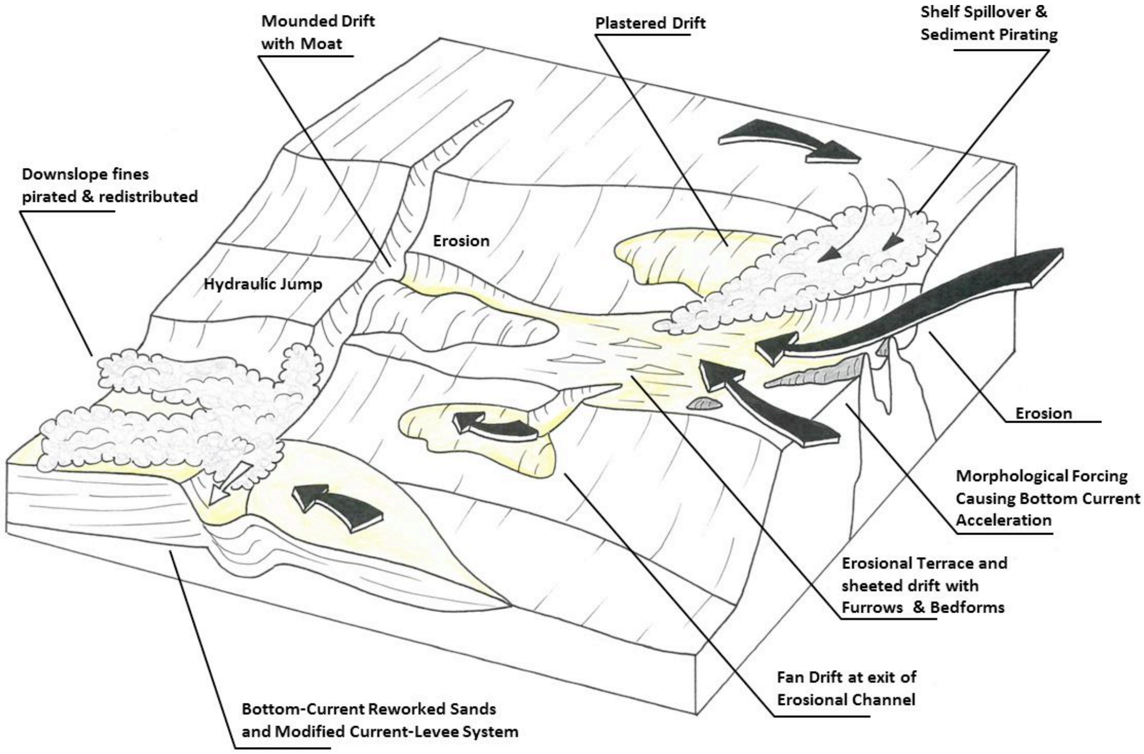


Figure 9.3: Various contourite sand and bottom current reworked sand depositional environments (sands indicated in yellow). Modified from Hernández-Molina et al. (2008).

9.1.2.2 Sheeted Drift Sands

Only rare examples of sand-dominated sheeted contourite drifts exist in the modern ocean on account of the high bottom current velocities that are required for their formation. One is identified below the modern day erosional terraces in the eastern Gulf of Cadiz sandy contourite depositional system (Antich et al. 2005; Stow et al. 2011), and an example has also been identified off the NW UK Continental Margin (Stow et al. 2002a). They are formed by vigorous tabular bottom currents, and additionally can also associated with pycnoclines and internal waves. In the Gulf of Cadiz, vigorous bottom currents are accelerated through the Gibraltar Gateway eroding the bedrock. Upon exiting the Gateway, they decelerate and deposit sand and gravel sediment. Finer-grain sizes are transported away and deposited either down-current or in drifts adjacent to the main bottom water core. The resulting deposit is a moderately clean sand deposit, reaching over 75 % sand in the proximal scours and ribbons sector of the Gulf of Cadiz (Nelson et al. 1993). The study here shows that the sheet displays a complex array of depositional features including contourite channels and associated mounded and plastered drifts, furrows and sediment waves. Accumulation can reach significant thicknesses, and on burial is predicted to maintain good porosity and permeability. The eastern Gulf of Cadiz sands are thought to be in excess of 800 m in thickness (Buitrago et al. 2001; Antich et al. 2005). Regions of bottom current acceleration through narrow conduits evidently provide a mechanism for impressive contourite sand accumulation (Fig. 9.3) and it may be this mechanism that resulted in the Pliocene deposition of seismic unit PQ along the Algarve Margin on exiting a very active region of diapirism in the north of the Gulf of Cadiz. Here, the sandy sediment is thought to source locally from downslope (debrite) deposits.

9.1.2.3 Contourite Mounded and Plastered Drifts

These are the least likely sandy contourite deposits to consist of good, clean sands and are of little interest to the petroleum industry as conventional reservoirs (Fig. 9.3). They may however form good unconventional reservoirs. Mienert et al. (2005) note their susceptibility for gas hydrate accumulation. Discrete layers of sandier sediment may be found within a broadly mud- or silt-dominated drift that correspond to times of enhance bottom current enhancement. These interbedded layers are rarely well preserved on account of high bioturbation rates in contourite drifts, and as a result are very poorly sorted in nature with only rare bedforms preserved (Table 9.1).

9.1.2.4 Fan Drifts

Contourite fans are formed at the exit of channels (Fig. 9.3). Upon exiting a confined channel, a bottom current core will spread out and decelerate, thereby reducing its transport capacity and depositing its sediment (Faugères et al. 2002a). These can be associated with contourite channels as is the case with the Vema contourite fan offshore Brazil (Mézarais et al. 1993; Faugères et al. 2002a). In rare occurrences, contourite currents can be captured by downslope channels. Such systems have ample supply of coarse shelf material, which when combined with the winnowing action of contour currents, can lead to good sand deposits in the associated fan drift at the channel exit. An example of such a deposit is found in the lowerslope of the Gulf of Cadiz (Habgood et al. 2003; Mulder et al. 2003; Hanquiez et al. 2010). Here, thin sandy lobes are massive in nature and consist of clean silts and fine sands (Mulder et al. 2008).

9.1.2.5 Mixed Systems and Bottom Current Reworked Sands

Mixed systems such as the Pliocene system offshore the Algarve Margin in the Gulf of Cadiz provide a further reservoir facies for hydrocarbon exploration (Fig. 9.3). The interplay of clastic influx with strong current reworking can produce well-sorted sandy accumulations with excellent reservoir potential. The Pliocene of the Algarve Margin shows promising signs of sand-rich contourite deposition, particularly seismic unit P2. It is made up of high amplitude reflections when compared to other units and shows evidence of a high-energy environment of deposition (erosional truncation of reflections is seen in the uppermost Pliocene). Where contourite-turbidite mixed systems can be identified in the subsurface, bottom current reworking of clastic downslope sediment holds the potential for excellent reservoir quality facies. This has also been demonstrated in the Santos Basin offshore Brazil (Viana et al. 1998; Viana and Rebesco 2007; Bulhões et al. 2012). Here, sediment overflow from the shelf directly feeds into the bottom currents. Additional modified downslope systems are seen where they are deposited in the path of vigorous alongslope currents. This results in regions of high amplitude acoustic response and large-scale bedforms where contourite sands are deposited. Along the Algarve margin, Seismic Unit P2 shows seismic evidence of this process, with major sediment influx up-current (debrites represented by chaotic seismic facies) resulting in the deposition of a sand-rich sheeted contourite drift downcurrent and basinwards (Fig. 6.2).

An alternative reservoir facies deposited here could be winnowed turbidite deposits or bottom current reworked sands (Shanmugam 2012b). Where downslope processes, generally occurring on a timescale of minutes to days, are influenced by much longer-lasting (operating of a geological timescale) moderate bottom currents, the finer grain sizes may be removed by winnowing. Often associated with sand-rich contourite depositional systems, bottom current reworked sands are found along continental margins where bottom currents are long-acting but reach insufficient velocities to completely dominate over downslope processes. Since the majority of bottom currents have velocities in the order of <30 cm s^{-1}, they will preferentially pirate the fine portion of the turbidite sediment (muds and silts) and the coarse portion will remain in place on the turbidite levee or fan (Armishaw et al. 1998; Stow et al. 2002a) (Fig. 9.3). The result is a sand-rich deposit exhibiting good sorting, porosity and permeability, and therefore good potential reservoir properties on burial are expected. If there was any minor onset of the MOW in the Lowermost Pliocene along the Algarve Margin (seismic unit P1 in chapter 8), this turbidite deposit could consist of reworked sands and hold some reservoir potential. Examples of such deposits have been identified both on the sea bed (Shanmugam and Moiola 1982) and in the subsurface (Mutti et al. 1980). A large body of work on bottom current reworked sands has been compiled in the Gulf of Mexico (Shanmugam 2012b) and examples are also identified in the South China Sea (Gong et al. 2012). Other bottom current reworked sands are found where bottom currents route down turbidite channels such as those seen in the Gulf of Cadiz (Habgood et al. 2003).

These deposits are of great interest to the hydrocarbon industry on account of their clean nature and associated reservoir potential. There are producing fields off the Brazil Margin that appear to be deposited by such processes (Moraes et al. 2007). The resulting facies often show some preservation of sedimentary structures such as traction surfaces and mud drapes (Fig. 9.12) (Shanmugam 2006), perhaps due to repeated influx of turbidity currents that prevent bioturbation to occur to any destructive level. However, there is still considerable controversy over the interpretation.

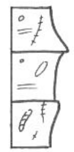
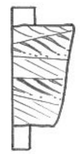
Contourite Sand Type	External Morphology	Distribution	Facies		Reservoir Quality
Contourite channel deposits	Alongslope erosional channel fill	Linear features, generally oriented alongslope.	Coarse clean sands, often showing cross-bedding / laminations.		Φ = good *Kv =good* *Kh=good*
Sheeted drift sands	Aggradational sheeted drift morphology	Laterally extensive	Massive sands and interbedded finer facies.		Φ = good *Kv =good* *Kh=good*
Contourite mounded, plastered or fan drifts	Progradational mounded drift morphology	Elongate alongslope. Sands often closely associated with contourite channels	Discrete beds and lenses of silty/muddy sands. Massive – bioturbated.		Φ = poor - moderate *Kv =poor* *Kh=good*
Bottom Current Reworked Sands	Modified downslope fan / levee system	Reworking in alongslope direction – often associated with downslope fan systems	Highly variable: sedimentary structures common. Mud drapes.		Φ = variable *Kv =poor* *Kh=variable*
Internal Tide Sands	Downslope channel or canyon fill	Contained within downslope channels and canyons	Highly variable: structures common. Mud Couplets.		Φ = poor-moderate *Kv =poor* *Kh=poor*

Table 9.1: Key features of different contourite sand deposits.

9.1.3 Other Potential Contourite Reservoir Facies

There has been some discussion in the literature of the potential of other contourite facies being economically important. Other potential contourite reservoirs being considered are calcicontourites (Viana and Almeida Jr. 2012), gas hydrates (Shao et al. 2007) and unconventional gas and oil shale reservoirs (Viana and Almeida Jr. 2012). Detailed studies are yet to assess whether these would make viable exploration targets and is an area for further work.

Carbonates are increasingly being thought of with bottom current reworking in mind thanks to their identification in the ancient record and on the modern sea floor. Chalks are expected to be of greatest reservoir potential and chalk contourites have been identified at outcrop scale (Hüneke and Stow 2008; Stow et al. 2002d) and in the subsurface (Surlyk and Lykke-Andersen 2007; 2008; Rasmussen and Surlyk 2012). Subsurface examples from the Danish and Paris Basins reveal that bottom currents reworked and eroded the North Sea Chalks of the Upper Cretaceous, forming erosional channels and giant elongate mounded drifts (Fig. 9.4 A).

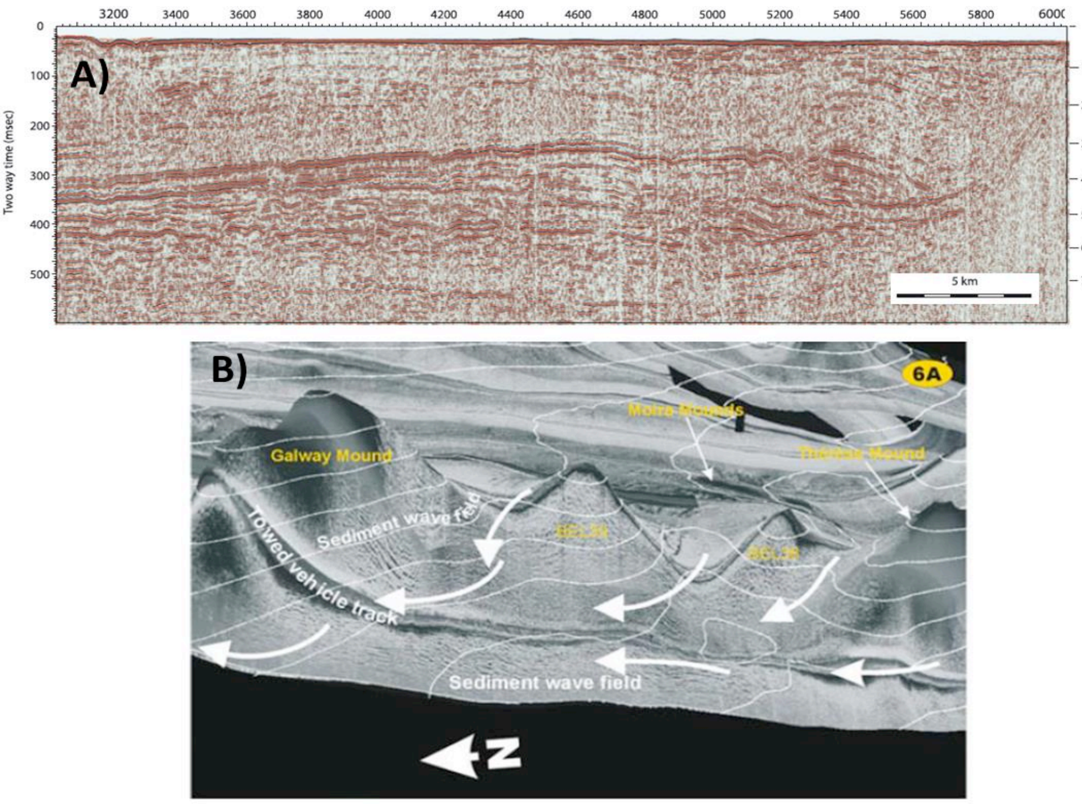


Figure 9.4: A) An elongate mounded chalk contourite drift from the Upper Cretaceous Danish Basin. From Surlyk and Lykke-Andersen (2007). B) Three-dimensional view of the Belgica Mounds in the NE Atlantic Ocean using side-scan draped on bathymetric data. White arrows indicate bottom current flow, and the side-scan sonar clearly shows sand wave formation on the sea floor adjacent to these mounds. From Wheeler et al. (2005).

Other potential carbonate reservoirs include cold water reefs, where intensifying bottom currents promote growth by providing nutrients and food flux to reef organisms, and winnow away fines (Bjeranger et al. 2010). Cold water coral mounds often form along the routes of vigorous currents that have created hard-grounds for coral settling and growth (Huvenne et al. 2009). The coral mounds themselves are expected to have moderate reservoir properties upon burial (subject to diagenesis), but are not expected to be laterally extensive enough to be economically viable on their own. Only where they are associated *with* other contourite facies may they be economic. Coral mounds can form spectacular steep-sided obstacles on the sea floor that can amplify bottom currents and result in associated sand deposition (Fig. 9.4 B) (Wheeler et al. 2005; Huvenne et al. 2009).

9.1.4 Contourite Reservoir Identification

9.1.4.1 Seismic Recognition

A first step to hydrocarbon exploration is on a basin scale. Therefore identification of potential contourite reservoirs in seismic data is paramount. This is extremely challenging on account of the fact that the countourite drifts that show significant external morphology and internal architecture (and are thus easily identified) tend to be muddy in composition. However, with the identification of buried mud-rich mounded contourite drifts, the knowledge of palaeocurrents sweeping the margin is gained. There may be associated sans-rich deposits alongslope and further investigation is recommended. Evidence for contourite sands must be gathered;

1) 2D seismic data can be used to identify any seismic units that are elongate in an alongslope orientation. Of particular interest are those turbidite systems that have been re-orientated oblique or along slope.
2) Contourite channels may be imaged on 2D data. They tend to be orientated alongslope, closely associated with contourite depositional features, u-shaped (often asymmetric) in cross section and filled with chaotic seismofacies (channel fill sands and gravels).
3) Where 3D seismic data can be used, more subtle distinguishing features may be identified such as sediment waves, sediment dunes, sand ribbons and furrows. Seismic amplitude mapping of surfaces can extenuate such feature as has been demonstrated along the Brazil Margin by Viana et al. (2007) (Fig. 9.5). Such features can be associated with sandy sheeted drifts and other sand-rich contourite deposits

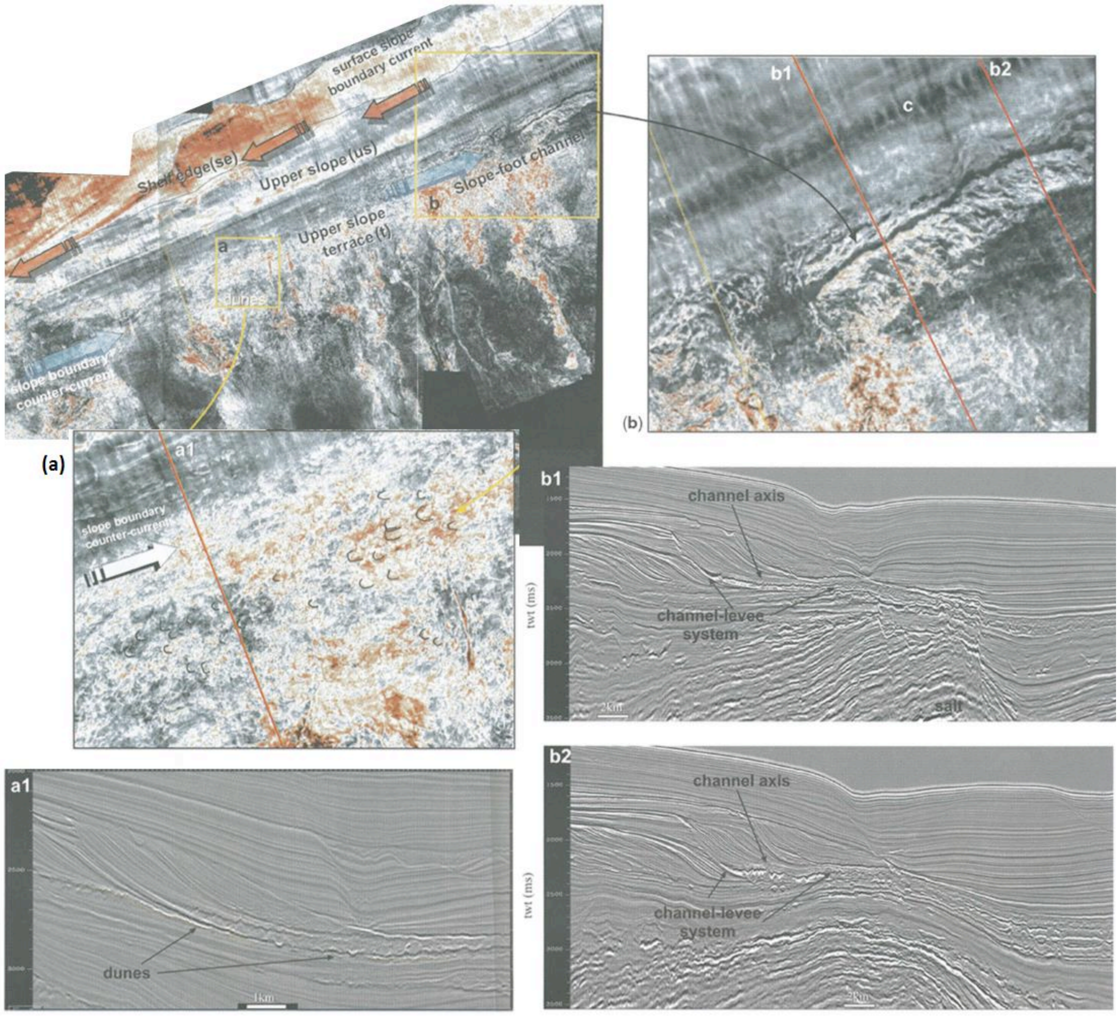


Figure 9.5: Some depositional and erosional features observed along the Brazil Margin in 3D seismic data. Main map (top left) show a RMS seismic amplitude map of the Late Eocene. Map approx. 100 m across and shows a variety of sediment waves drifts and erosional alongslope-orientated channels. Modified from Viana et al. (2007).

9.1.4.2 Sediment Facies Recognition

It is impossible to provide a clear set of diagnostic criteria for contourite sands. Rather a number of observations must be made that point towards contourite sedimentation as a likely depositional process. Core and sediment data should always be used closely with seismic data to build evidence for the depositional process. Key features to identify are;

- Reverse and normal grading – particularly close to erosional surfaces.
- Erosional surfaces with subtle grading above and below
- High bioturbation rates within associated finer facies
- Localised laminations and/or cross lamination.

Only limited core examples of contourite from the subsurface exist, and are generally of the Brazilian Margin examples from the Campos and Santos Basins. Figure 9.6 shows one such example of contourite sands that show localized laminations. They are closely associated with highly bioturbated muds and silts.

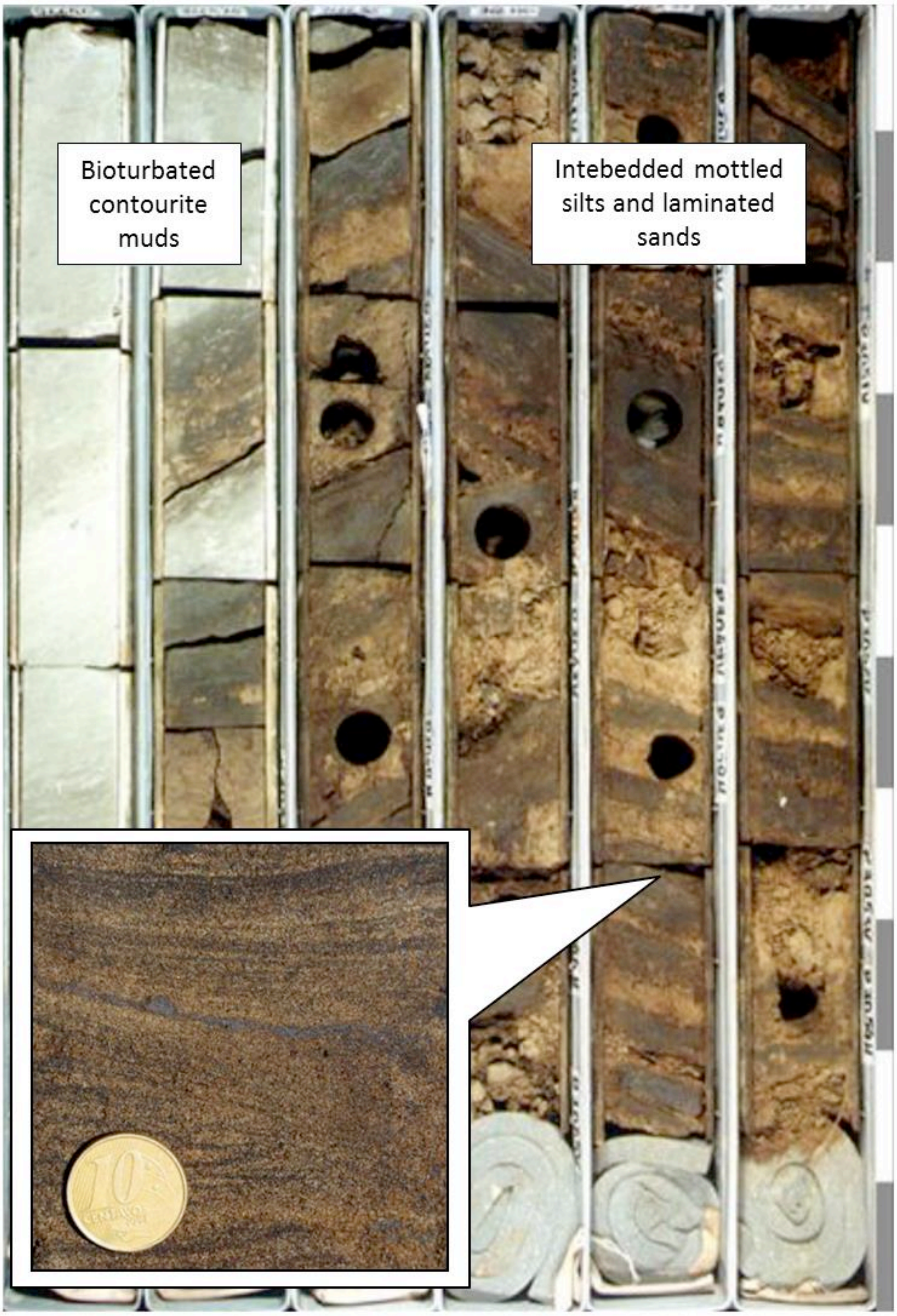


Figure 9.6: Highly cyclic sands with bioturbated silts. Note close association with completely reworked mudstones. Example form the Brazilian Margin well 8-BR-18D-RJS T-02 sections CX-01 – CX-06. Modified from Mutti and Carminatti (2012).

9.2 Other Petroleum System Aspects

A first step in any hydrocarbon exploration is basin analysis. That is, the study of a basin in order to predict the existence of petroleum play elements and examine the timing of processes to determine viability of hydrocarbon system development (Allen and Allen 1990). In recent years, deep water prospects along divergent margins have been highly productive since the process of rifting and the post rift passive margin succession lend themselves to source, reservoir, seal and trap formation. Contourite depositional systems commonly form along divergent continental margins (Hernández-Molina et al., 2008) and basin analysis shows there is a strong likelihood that contourite depositional systems should be capable of providing many of the necessary aspects for a functioning hydrocarbon system (Fig. 9.7) (Stow et al., 2010). Aspects of the petroleum play are outlined below with contourites in mind.

9.2.1 Source Rock

In any petroleum system, the source rock is generally the most poorly understood aspect. This is precisely the same with contourite potential source rocks, and there is no conclusive evidence for or against the source potential of fine-grained contourite accumulations. Viana (2008) state that the ventilation that bottom currents provide is not suitable for the accumulation of high TOC sediment. This is direct conflict with the same authors suggestion that unconventional reservoirs in America may be of contouritic origin (Viana and Almeida Jr.

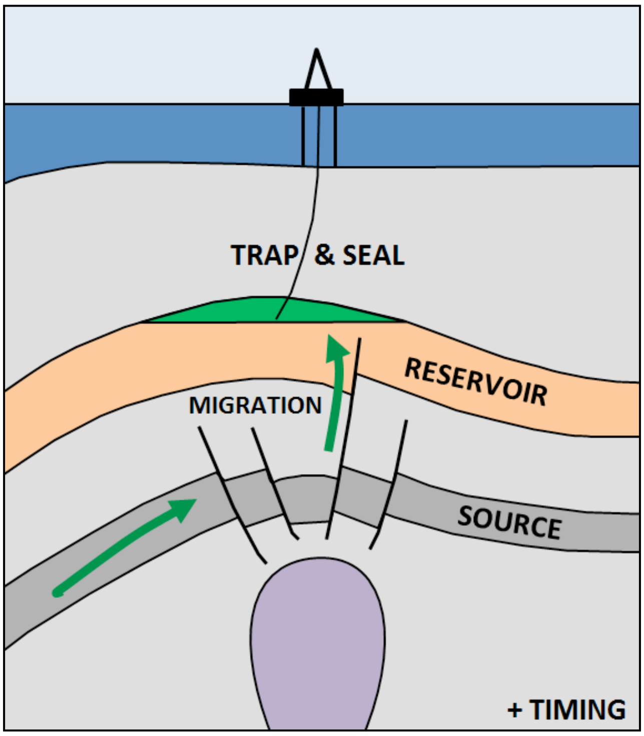


Figure 9.7: Aspects of a successful petroleum system. A generating source, migration pathway, reservoir, trap and seal are all required. Timing is also crucial to success.

2012) and therefore have the capability of producing hydrocarbons upon maturation. Other authors argue that higher TOC values can be a distinguishing feature of contourites when compared to distal muddy turbidites (Potter et al., 2005). Fine-grained contourites certainly provide several conditions favourable to the preservation of organic matter, for example rapid burial rates, fine-grain sizes and potential high organic matter influx (Stow et al., 2001). An additional source rock consideration is that of gas hydrates that form in many active contourites on the sea bed (Viana et al., 2008). More work is required in this field.

9.2.2 Seal

For a facies to form an effective seal, a low porosity and permeability is required. This will help the capillary displacement pressure of the rock to exceed the hydrocarbon buoyancy pressure and thus prevent upward migration (Allen and Allen 1990). Where sandy contourites accumulate, changes in climate, eustasy, or margin morphology can result in a change in the hydrodynamic regime. If this reduces the bottom current velocity, either by a change in the driving force or a relocation of the water core, then muddy contourite deposition will prevail. Where the bottom current is reduced further, or completely turned off, pelagic, hemipelagic or downslope processes may become dominant. All these deposits can be very fine grained and provide an effective regional topseal. Laterally, sandy contourites will become more mud rich, diminishing in reservoir quality and providing lateral seals (Viana et al., 2007).

9.2.3 Trap Formation

Continental margins provide several opportunities for hydrocarbon trap formation, and as a result, exploration along the continental slopes has been highly active and prosperous in the last few decades. Contourite reservoirs can be expected to be influenced by the same trapping mechanisms. The lateral grading of reservoir quality facies to mud-dominated in all directions in a contourite drift, lends itself to stratigraphic trapping (Viana, 2008).

Contourite systems have the capacity to provide all the required aspects for a functioning petroleum system, evidenced by high profile examples from the Campos Basin (Mutti et al., 1980; Moraes et al., 2007; Viana et al., 2008). Other examples include contourites from the Gulf of Mexico (Shanmugan 1993; 1995), North Sea (Enjorlas at al., 1986), and the Gulf of Cadiz (Cakebread-Brown et al., 2003; Fernández-Puga et al., 2007). There is a strong likelihood that many more examples exist, but have been incorrectly interpreted as turbiditic and other deposits. Such reservoirs may be of contouritic origin but the recognition of such facies does not yet utilise clear diagnostic criteria. This research aims to characterise potential reservoir contourite beds to aid identification in core and seismic data (Stow et al., 2011).

9.3 Discussion

This study reveals that contourite sands of good potential hydrocarbon reservoir quality are deposited only within specific environments within a sandy contourite depositional system. A preferred hydrocarbon reservoir shows good porosity, good vertical and horizontal permeability, and good lateral and vertical continuity between sand bodies. The results from this study show good lateral continuity of beds across the drifts, but the intense bioturbation in these depositional environments has had a catastrophic effect on the sediment sorting, and therefore the poroperm values upon burial are expected to be low (Table 9.1). Clean sands (>70 % sand) accumulate over wider areas of the sea bed as sheeted drifts. Contourite channels show the best quality sands, clean and often very coarse (>500 µm) but are of limited lateral extent (Table 9.1). Where bottom currents reach sufficient velocities, sand is deposited and mud and silt-sized particles are flushed out of the system. The resulting deposit is expected to show excellent reservoir potential on burial. A subsurface example has been examined in detail in the Campos Basin (Viana et al., 2007).

Carbonate contourite reservoir rocks are comparatively less researched and understood. However, recent work in the Danish Basin shows evidence for what is undoubtedly contourite activity in the Upper Cretaceous chalk succession (Surlyk and Lykke-Andersen, 2007). Such a discovery opens up the possibility of contourite chalks being potential reservoirs, and this idea is already being explored in the Cretaceous chalk reservoirs in the North Sea (e.g. Spencer et al., 2008).

The industry interest in contourites is rapidly gathering pace. Within the last seven years, there has been one special volume publication (Viana and Rebesco 2007), numerous conference talks (Bulhões et al. 2012; Stow et al. 2011; Viana and Almeida Jr. 2012) and one industry workshop (Brackenridge et al. 2013a). Buried contourite mounded drifts of Paleocene in age have been identified along the Brazilian Margin, (Mutti et al. 1980; Moraes et al. 2007), Newfoundland Margin (Expedition 342 Scientists 2012), and the African Margins (Thompson pers.comm.) with additional buried mounded drifts identified in the Miocene offshore New Zealand (Fulthorpe et al. 2010) and Cretaceous Danish Basin (Surlyk and Lykke-Andersen 2007). Although these mounded drifts are generally composed of mud or chalk, It is clear that bottom currents have been active in the geological past at velocities capable of redistributing and depositing sandy sediment. These sand-rich deposits have, as yet, only been positively identified in the subsurface in a very few cases (Mutti et al. 1980; Enjorlas et al. 1986; Moraes et al. 2007) and undoubtedly more have been misidentified as turbidite sands. This is largely due to poor understanding of the preservation of defining features and a lack of a robust set of diagnostic criteria. This thesis presents the most up to date understanding of contourite sand characteristics and importance to date. The lack of clear identification criteria has led to the petroleum industry seeking other reservoirs over the last three decades – mainly turbiditic in deep water settings.

Accurate identification of contourite facies, and their distinction from other deep water sands will have great consequences for the de-risking of exploration targets, as well as aiding well planning, basin modelling and production strategy. Ultimately, the recoverable reserves may be significantly reduced if reservoir models are populated with parameters more akin to turbidite reservoirs as sand distribution, and permeability parameters will be misinterpreted.

9.4 Conclusions

Bottom currents pose a very real threat to subsea activity along continental margins and it is important that oceanographic conditions are carefully considered prior to deep water operations to ensure the work can be carried out safely. Despite these hurdles to deep water exploration along continental margins – it is becoming increasingly clear that upon burial, contourites *do* have the potential make successful hydrocarbon reservoirs. Continental margins can provide many aspects of a petroleum system. Deep water continental margins offer mature source rocks, ample seal facies and trapping structures. The search for reservoir facies in the past has focused on turbidite systems, which are capable of supplying sand-facies to the continental slope. Turbidite sand sheets are often regarded to be among the most economical reservoirs on account of their excellent lateral continuity, simple reservoir geometry, and well sorted sediments (Weimer and Slatt 2004). Now, contourite sands are showing increasing reservoir potential. Sand sheets and contourite channels show the best reservoir potential.

The Gulf of Cadiz and other sand-rich contourite depositional systems show there can be sufficient transport capacity in a given bottom current for the transport and deposition of grain sizes >0.63 μm, and that if there is a sediment influx from the shelf to a bottom current system, then there is the possibility of accumulating contouritic sediments on the slope that have very attractive properties for the hydrocarbon industry. Since misinterpretation of contourite deposits has important implications for reservoir architecture and reservoir modelling, it is of great importance that contourite sand sheets are identifiable in geophysical and core data. For a robust identification to be made, the explorationist should take care to observe external and internal morphologies of sediment bodies in seismic data in addition to reconstructing the margin paleoceanographic set-up in order to fully determine the origin of a potential reservoir target.

Conclusions & Further Work

10 Further Work & Conclusions

10.1 Further Work

In 2013, the fiftieth anniversary of the first 'contourite' paper came and went with little acknowledgement. It documented the first evidence that deep water currents were capable of reworking the sea floor (Heezen and Hollister 1963). Since that time, much progress has been made by marine geologists and physical oceanographers to understand contourite depositional systems and the currents that form them (see Section 2.1) (Rebesco et al. 2014). In spite of this, there are still a number of key unanswered questions remaining in contourite science;

1) *Nature of bottom water flow:* Exactly how do bottom currents relate to those features seen on the sea floor? How does the flow affect the bedforms observed and the controls on mounded and sheeted drift formation? How does the cyclicity of bottom current velocity (both long-term and short-term cyclicity) determine the deposit observed on the sea floor?
2) *Mechanics of deposition from bottom currents:* What are the controls on bed load vs. suspended load portions within the benthic layer? Are high energy events such as benthic storms required for the re-suspension of material from the sea floor? Can grain size be used as a proxy for bottom water flow velocity?
3) *Sedimentary characteristics:* Where are all the contourites in the geological record? What key distinguishing features are seen at core- and outcrop-scale to positively identify contourites?
4) *Bioturbation vs. sedimentary structure preservation:* Why are contourites so void of preserved sedimentary structures? Is there a specific ichnofacies associated with contourite sedimentation? Is bioturbation linked to rates of sediment accumulation?
5) *Seismic characteristics:* What causes the cyclicilty observed in contourite drifts? What seismic facies can be used to aid the identification of sheeted drifts? How does the seismic response relate to the sedimentary record?
6) *Reservoir potential:* Could contourite sands be the next frontier hydrocarbon exploration target? What is their reservoir potential upon burial and how can they be positively identified and found in the subsurface?

This research has gone some way to answering some of these remaining questions, but many more require further work. Here, recommendations on further work based on this research thesis are outlined.

10.1.1 The Gulf of Cadiz Contourite Depositional System

Chapter 6 makes presents a new model for past MOW activity and contourite evolution in the eastern Quaternary section of the Gulf of Cadiz, and a new interpretation of a Pliocene buried mixed system and associated sheeted drift along the northern margin. Outstanding questions from the work on the eastern Gulf of Cadiz sandy contourite depositional system include;

- Where are the key sediment provenances and sediment influx routes into this CDS? It is clear from compositional data that there is changing sediment provenance over time, but what are they? A full analysis of mineralogy and heavy mineral content is recommended to further understand the sediment budget of the system both in the eastern Gulf of Cadiz, and the wider Gulf of Cadiz margin.
- What did the eastern Gulf of Cadiz look like prior to the onset of 10,000 year climatic cycles? It is clear from the study in the northern Gulf of Cadiz that the Mid-Pleistocene Revolution played an important role in changing the depositional features of the margin. How did it affect the contourite sands most proximal to the Gibraltar Gateway?

The Algarve Margin in the north of the Gulf of Cadiz has some remaining questions also standing. Over the course of this thesis research, sediment cores were collected from the region onboard IODP Expedition 339. These have not as yet been integrated with the seismic data and this is an area for further work.

The seismic data has also provided a great deal of information through the course of this study. Further work is recommended to link the two study areas and, with the new understanding presented in this thesis, present a fully integrated interpretation of the Gulf of Cadiz CDS with includes sectors 1-4.

10.1.2 Characterising Contourite Sands

This study uses an extensive data-set from the Gulf of Cadiz and provides one of the largest (if not *the* largest) sedimentological analyses of a single sand-rich contourite depositional system. This raises some important questions;

- Are the contourite sands in the Gulf of Cadiz representative of all other contourite sand depositional systems from around the globe? A review of the existing cores and sediment samples is recommended, including soft sediment modern examples from various margins and, if possible, industry subsurface cores.

- Can sediment grain size parameters be used to distinguish between different depositional processes without the need of other data? This can be tested using the newly acquired IODP Expedition 339 data to assess if cross plotting parameters such as sorting and skewness shows grouping of data relating to depositional process (contourite vs. turbidite vs. pelagic and so on). A first step to this has been attempted, but more accurate logging is required (Fig. 10.1).

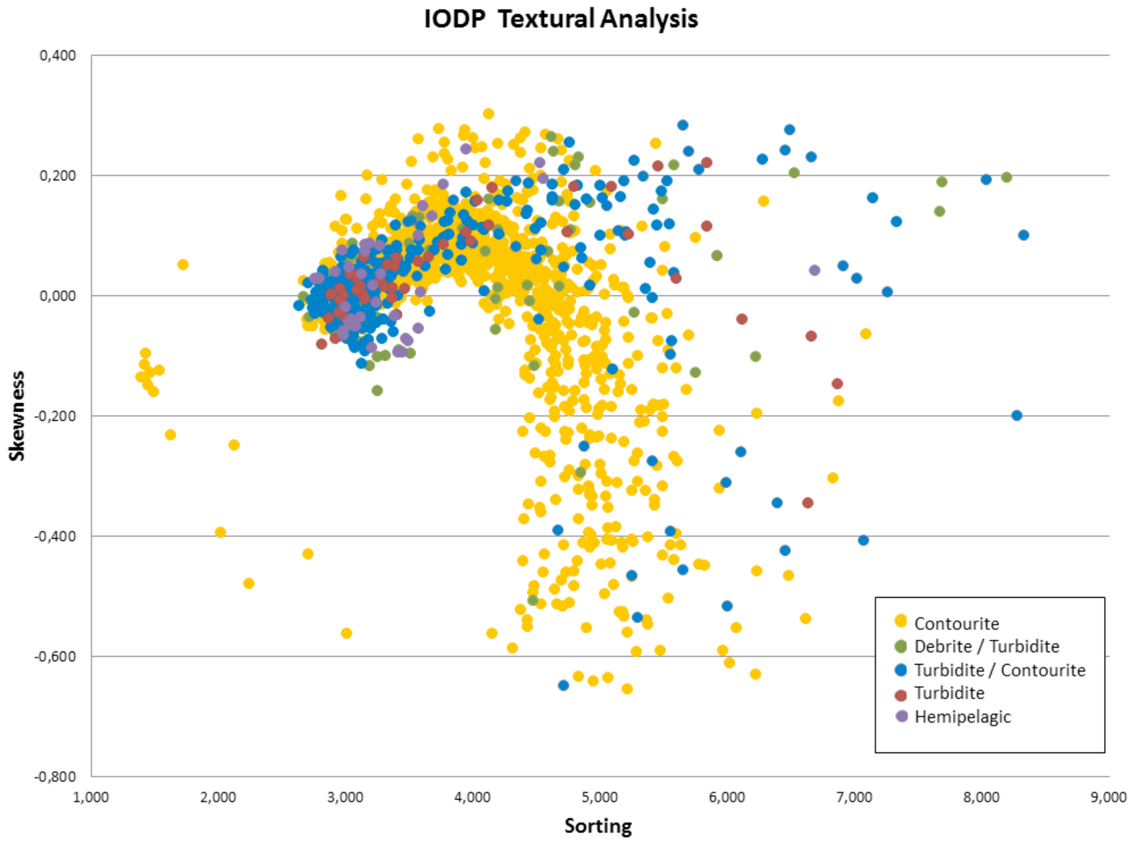


Figure 10.1: Preliminary analysis of IODP Expedition 339 textural analysis as divided by depositional environment.

10.1.3 Contourites within a Sequence Stratigraphic Framework

Although Chapter 8 has made a good first step towards the integration of contourites with deep water sequence stratigraphic models, there are still many unanswered questions and scope for further work;

- The models provide two end-members for a margin with smooth topography. What happens when there are large erosional terraces? Or stacked water masses affecting the margin?

- Where sediment supply into the basin is more restricted so that downslope processes cannot dominate, how does this affect the model?
- How does erosion affect accommodation space, and therefore stacking patterns? Erosion can cause local sub-basins along margins, how do these affect stacking patterns?
- This study examined sequence stratigraphic controls on contourite in general. But what about contourite sands specifically. Can this model be used to predict reservoir presence? If so, where would the best reservoir be deposited?

10.1.4 Contourite Reservoir Potential and Economic Importance

In reality, it is extremely difficult to make conclusions on the reservoir potential of contourite sands using modern day examples. A full industry-sponsored study is recommended that integrates global seismic data-sets with state-of-the-art ocean circulation and plate tectonic reconstructions to identify targeted areas with higher chance of contourite accumulations in the subsurface. Identification on seismic data-sets will lead to the identification of key wells for facies studies to be conducted. Building up a global data-set of contourite sand examples is key to determining their petroleum potential and promote industry interest. With more and more convincing examples coming from basins offshore Brazil, perhaps more companies will begin to look out for contourite sands in the future.

10.2 Conclusions

Despite the volume of remaining questions that future contourite scientists must tackle, some conclusions can be made based on this research. This study has interpreted a newly acquired data-set from the eastern Gulf of Cadiz and integrated it with vintage data from the wider continental margin to give a new understanding of sand-rich contourite depositional systems. A new interpretation of the Gulf of Cadiz contourite depositional system was presented in **Chapter 6**, focusing on a buried mixed system in the north of the study area and a modern day sand-rich contourite system in the east. From this, the sands were characterised in terms of facies and grain size parameters in **Chapter 7** with the aim of aiding identification of contourite sands elsewhere in the future. The controls of contourite sedimentation were assessed using the data from this study and literature review in **Chapter 8**, and a new sequence stratigraphic model proposed. Finally, all the interpretations were compiled and used with full literature review to make conclusions on the economic potential of sandy contourite depositional systems (**Chapter 9**).

From this research the following conclusions can be made;

I. The eastern Gulf of Cadiz sandy contourite depositional system has a previously unappreciated complexity comprising from the upper slope basinwards: 1) Upperslope plastered drifts; 2) A northern contourite channel with associated mounded drift; 3) Two midslope erosional and sand-dominated contourite terraces with, one upper and one lower, with an underlying sandy sheeted drift; 4) A southern channel and associated mounded drift; 5) A lower slope muddy sheeted drift dominated by sediment waves and 6) Lower slope contourite channels and associated fan drifts.

II. The MOW is much more mobile and variable than previously thought and there is evidence that it influenced the mid- and lowerslope during glacial conditions and the upper- and midslope during interglacials (as is seen today).

III. A mixed system and associated sheeted drift is identified in the Pliocene of the Algarve Margin (northern Gulf of Cadiz) that shows the changing dominance between downslope and alongslope processes over time.

IV. Contourite characterisation requires the integration of acoustic, core and sediment data. Palaeoceanographic and margin reconstruction is essential for building proof of contourite deposition in the subsurface.

V. There is no single contourite sand facies sequence model, and three new models have been proposed broadly relating to depositional energy. Key features are erosional surfaces, normal and reverse grading, and high bioturbation rates in the associated finer facies.

VI. Grain size distributions show fine-grained contourites are dominated by settling with a mainly hemipelagic settling supply, medium-grained contourites result from depositional processes from a mixed hemipelagic/alongslope supply, and coarse-grained contourites are significantly affected by erosional (winnowing) processes.

VII. Bottom currents can be more vigorous during lowstand or highstand depending on the bottom water source and local basin morphology. As a result, two end-member sequence stratigraphic models have been proposed.

VIII. For contourite sands to accumulate, key controls require it to have: 1) A sandy sediment supply, either from an alongslope or downslope provenance; 2) Favourable basin morphology to allow for the amplification of bottom currents; and 3) A strong bottom current that operates over a geological timescale.

IX. The best quality contourite sands are found in contourite channels, sheeted drifts and bottom current reworked sand accumulations. These make the best potential hydrocarbon reservoirs.

X. Accurate identification of contourite facies, and their distinction from other deep water sands will have great consequences for the de-risking of exploration targets, as well as aiding well planning, basin modelling and production strategy.

The interest in contourites and contourite sands has increased immensely over the course of completing this research thesis, with both industry and academic involvement in the contourite community growing year by year. The problem still stands that contourite sands remain highly elusive in the subsurface. To this end, a frequent question I have been asked over the course of this research is “do contourite sands really exist?” I respond with a quote popularised in 1830 by the pioneering geoscientist Charles Lyell;

“The present is the key to the past”

The modern day Gulf of Cadiz undeniably proves that contourite sands are actively forming today, and over an extensive area and are of considerable thickness. The fact that contourite sands are also found at other locations across the globe presently forming, and are actively producing hydrocarbons in the subsurface verifies that the Gulf of Cadiz is not a result of some Goldilocks effect of perfect conditions for contourite sand accumulation. Rather that these deposits are possible elsewhere. It is my belief that a poor identification criteria is the sole reason that there are not more examples of contourite sands in the subsurface. It is my hope that this research thesis, it’s accompanying published papers, and its many associated conference and workshop presentations will inspire geoscientists to keep contourites in mind when interpreting data at core, sediment, outcrop and sediment scale.

11 References

Akhmetzhanov, A., Kenyon, N., Habgood, E., Ven Der Mollen, A., Nielsen, T., Ivanov, M., and Shashkin, P. (2007). "North Atlantic contourite sand channels", in A. Viana and M. Rebesco, (eds.), *Economic and Palaeoceanographic Significance of Contourite Deposits.* London: Geological Society.

Alejo, I., Nombela, M., Ercilla, G., Brackenridge, R., Francés, G., Pérez-Arlucea, M., Mena, A., Hernández-Molina, F., Stow, D., and Medialdea, T. (2012). "Caracterización de los sedimentos superficiales en tres sistemas deposicionales contorníticos (Golfo de Cádiz, Cabo Ortegal y El Cachucho): implicaciones conceptuales. (Recent sediments characterization of three contourite depositional systems (Gulf of Cadiz, Ortegal Spur and El Cachucho): conceptual implications)." *Geo-Temas*, 13, 535-236.

Allen, P. (1997). *Earth Surface Processes*, Oxford: Blackwell.

Alves, T., Gawthorpe, R., and Hunt, D. (2003). "Cenozoic tectono-sedimentary evolution of the western Iberian margin." *Marine Geology*, 195, 75-108.

Ambar, I., Armi, L., Bower, A., and Ferreira, T. (1999). "Some aspects of time variability of the Mediterranean Water off south Portugal." *Deep-Sea Research Part I-Oceanographic Research Papers*, 46(7), 1109-1136.

Ambar, I., and Howe, M. (1979). "Observations of the Mediterranean Outflow 1. Mixing in the Mediterranean Outflow." *Deep-Sea Research Part a-Oceanographic Research Papers*, 26(5), 535-554.

Ambar, I., Serra, N., Brogueira, M., Cabecadas, G., Abrantes, F., Freitas, P., Goncalves, C., and Gonzalez, N. (2002). "Physical, chemical and sedimentological aspects of the Mediterranean outflow off Iberia." *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, 49(19), 4163-4177.

Amy, L., McCaffrey, W., Kneller, B., Lomas, P., and Lomas, S. (2004). "The influence of a lateral basin-slope on the depositional patterns of natural and experimental turbidity currents." *Deep-Water Sedimentation in the Alpine Basin of Se France: New Perspectives on the Gres D'annot and Related...* 221, 311-330.

Ananiadis, G., Vakalas, I., Kontopoulos, N., and Zelilidis, A. (2004). "Hydraulic and statistical grain-size parameters of Pindos turbidite deposits." *Bulletin of the Geological Society of Greece.*, 36, 689-698.

Antich, N., Buitrago, J., García Mojonero, C., Jiménez, A., and Martínez del Olmo, W. (2005). "Contourites: An unknown and excellent reservoir (Gulf of Cadiz, SW Spain).", in W. Martinez del Olmo, (ed.), *Libro 25 Aniversario*. Madrid: Associatión de Geólogos y Geofisicos Españoles del Petróleo (AGGEP), pp. 75-82.

Armishaw, J., Holmes, R., and DAV, S. (1998). "Hebrides slope apron and Barra fan, NW UK continental margin sedimentation.", in M. Stoker, D. Evans, and A. Cramp, (eds.), *Geological Processes on Continental Margins.* London: Geological Society, pp. 81-104.

Ashi, J. (1995). "CT scan analysis of sediment from Leg 146." *Proceedings of the ocean Drilling Program, Scientific Results*, 146, 1-11.

Bache, F., Popescu, S.-M., Rabineau, M., Gorini, C., Suc, J.-P., Clauzon, G., Olivet, J.-L., Rubino, J.-L., Melinte-Dobrinescu, M., Estrada, F., Londeix, L., Armijo, R., Meyer, B., Jolivet, L., Jouannic, G., Leroux, E., Aslanian, D., Tadeu Dos Reis, A., Mocochain, L., Dumurdzanov, N., Zagorchev, I., Lesic, V., Tomic, D., Cagatay, M., Brun, J.-P., Sokoutis, D., Csato, I., Ucarkus, G., and Cakir, Z. (2012). "A two step process for the reflooding of the Mediterranean after the Messinian Salinity Crisis." *Basin Research*, 24, 125-153.

Bagnold, R. (1973). "The nature of saltation and of 'bed-load' transport in water." *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences.*, 332(1591), 473-504.

Bahr, A., Jimenez-Espejo, F., Kolasinac, N., Auschill, S., Röhl, U., Hernández-Molina, J., Stow, D., Hodell, D., Alvarez-Zarikian, C., and Scientists, I. E. (2013). "Preliminary results from XRF scanning of contourite deposits in the Gulf of Cadiz (IODP Exp. 339).", M. Rogerson, S. Legg, D. Van Rooij, R. Brackenridge, B. Preu, D. Stow, and F. Hernádez-Molina, (eds.), *Dialogue Between Contourite and Oceanography Processes; International Workshop*. City: University of Hull, pp. 36.

Baldwin, C., and McCave, I. (1999). "Bioturbation in an active deep-sea area: implications for models of trace fossil tiering." *Palaios*, 14, 375-388.

Baraza, J., Ercilla, G., and H. Nelson, C. (1999). "Potential geologic hazards on the eastern Gulf of Cadiz slope (SW Spain)." *Marine Geology*, 155(1-2), 191-215.

Baringer, M., and Price, J. (1997). "Mixing and spreading of the Mediterranean outflow." *Journal of Physical Oceanography*, 27(8), 1654-1677.

Baringer, M., and Price, J. (1999). "A review of the physical oceanography of the Mediterranean outflow." *Marine Geology*, 155(1-2), 63-82.

Bender, V., Hanebuth, T., Mena, A., Baumann, K.-H., Francés, G., and von Dobeneck, T. (2012). "Control of sediment supply, palaeoceanography and morphology on late Quaternary sediment dynamics at the Galician continental slope." *Geo-Marine Letters*, 32, 313-335.

Bjeranger, M., Surlyk, F., Lykke-Andersen, H., Thibault, N., and Stemmerik, L. (2010). "Danian cool-water coral reefs in southern Scandinavia localised over seafloor highs. ." *Marine and Petroleum Geology*, 27(2), 455-466.

Blakey, R. (2011). "Global Paleogeography.". City: http://www2.nau.edu/rcb7/260moll. jpg.

Blanc, P. (2002). "The opening of the Plio-Quaternary Gibraltar Strait: assessing the size of a cataclysm." *Geodinamica Act*, 15, 303-317.

Blott, S., and Pye, K. (2001a). "GRADISTAT". City: http://onlinelibrary.wiley.com/doi/10.1002/esp.261/suppinfo.

Blott, S., and Pye, K. (2001b). "GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments." *Earth Surface Processes and Landforms*, 26, 1237-1248.

Borenas, K., Wahlin, A., Ambar, I., and Serra, N. (2002). "The Mediterranean outflow splitting - a comparison between theoretical models and CANIGO data." *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, 49(19), 4195-4205.

Brackenridge, R., Essex, H., Juan, C., and Vandorpe, T. "Workbook and Fieldguide." *Presented at INQUA Project 1204: Contourite Core Workshop*, British Ocean Sediment Core Research Facility, Southampton

Brackenridge, R., Hernández-Molina, F., Stow, D., and Llave, E. (2013b). "A Pliocene mixed contourite-turbidite system offshore the Algarve Margin, Gulf of Cadiz: seismic response and implications for the evolution of the margin." *Marine and Petroleum Geology*, 46, 36-50.

Brackenridge, R., Hernández-Molina, F., Stow, D., Llave, E., and Team, C. (2013c). "Sediment study of the Gulf of Cadiz modern sandy sheeted drift: Preliminary results."*Dialogue Between Contourite and Oceanographic Processes: International workshop.* City: Hull, UK, pp. 62.

Brackenridge, R., Hernández-Molina, F., Stow, D., Mena, A., Alejo, I., Ercilla, G., Francés, G., Llave, E., Nombela, M., Perez-Arlucea, M., and CONTOURIBER Team. (2013d). "A contourite sand sheet east of the Strait of Gibraltar; a sedimentological study revealing the complexity of high energy bottom water systems in the Gulf of Cadiz."*International Association of Sedimentologists, Annual Meeting 2014*. City: Manchester, UK.

Brackenridge, R., Stow, D., and Hernández-Molina, F. (2011). "Contourites within a deep-water sequence stratigraphic framework." *Geo-Marine Letters*, 31, 343-360.

Brackenridge, R., Stow, D., and Hernández-molina, F. (2010). "Contourites in the deepwater sequence stratigraphic framework." *Geo-Temas*, 7, 17-18.

Brackenridge, R., Stow, D., Hernández-Molina, F., and Llave, E. (2012). "The seismic expression and evolution of a buried sheeted drift within the Algarve Basin (Gulf of Cadiz)." *Geo-Temas*, 13, 541.

Bridge, J., and Demico, R. (2008). *Earth Surface Processes, Landforms and Sediment Deposits.*, Cambridge: Cambridge University Press.

Bromley, R. (1996). *Trace Fossils: Biology, Taxonomy and Applications*, London: Chapman and Hall.

Bryden, H., Longworth, H., and Cunningham, S. (2005). "Slowing of the Atlantic overturning circulation at 26°N." *Nature*, 438, 655-657.

Buitrago, J., Garcia, C., and Cakebread-Brow, J. (2001). "Contouritas: Un excelente almacén casi desconocido (Golfo de Cádiz, SO de España)."*1er Congreso Técnico Exploración y Producción REPSOL-YPF. Septiembre 2001*. City: Madrid, pp. 24-27.

Bulhões, E., Freitas, J., Castro, M., Vasconcellos, C., Madeira, C., Carminatti, M., and Mutti, E. (2012). "The interaction between gravitational flows and contourite currents in the Oligocene of the Santos Basin, Brazil."*VIII Congreso Geólogico de Espana*. City: Geo-Temas: Oviedo, Spain, pp. 539.

Cabecadas, G., Brogueira, M., and Goncalves, C. (2002). "The chemistry of Mediterranean outflow and its interactions with surrounding waters." *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, 49(19), 4263-4270.

Cacho, I., Grimalt, J., Sierro, F., Shackleton, N., and Canals, M. (2000). "Evidence for enhanced Mediterranean thermohaline circulation during rapid climatic coolings." *Earth and Planetary Science Letters*, 183(3-4), 417-429.

Campillo, A., Maldonado, A., and Mauffret, A. (1992). "Stratigraphic and tectonic evolution of the western Alboran Sea: Late miocene to recent." *Geo-Marine Letters*, 12, 165-172.

Candela, J. (2001). "Mediterranean water and global circulation.", in G. Sedler, J. Church, and J. Gould, (eds.), *Ocean Circulation and Climate Observing and Modelling in the Gloabl Ocean.* Burlington: Academic, pp. 419-429.

Carter, L., Carter, R., and McCave, I. (2004). "Evolution of the sedimentary system beneath the deep Pacific inflow off eastern New Zealand." *Marine Geology*, 205(1-4), 9-27.

Catuneanu, O. (2006). *Principles of Sequence Stratigraphy*, Amsterdam: Elsevier.

Catuneanu, O., Abreub, V., Bhattacharya, J., Blum, M., Dalrymple, R., Eriksson, P., Fielding, C., Fisher, W., Galloway, W., Gibling, M., Giles, K., Holbrook, J., Jordan, R., Kendall, C., Macurda, B., Martinsen, O., Miall, A., Neal, J., Nummedal, D., Pomar, L., Posamentier, H., Pratt, B., Sarg, J., Shanley, K., Steel, R., Strasser, A., Tucker, M., and Winker, C. (2009). "Towards the standardization of sequence stratigraphy." *Earth-Science Reviews*, 92(1-2), 1-33.

Clare, M. "Contour currents and their deposits - a geohazards perspective." *Presented at INQUA Contourite Core Workshop for Early Career Scientists*, BOSCORF, Southampton.

Cooper, J. (1998). "Particle Size Analysis - The Laser Diffraction Technique." *Materials World*, 6, 5-7.

CSIC Unidad de Tecnologia Marina. "B/O Sarmiento de Gamboa: Equipamiento". City: http://www.utm.csic.es/sarmiento_equ.asp.

Dall'Olio, E., Falletti, F., and Muttoni, G. "Hemipelagites, hemiturbidites or muddy contourites? The contribute of magnetic fabric analysis to discriminate depositional mechanisms in fine-grained sediments (Marnoso Arenacea Fm., Miocene, northern Italy)." *Presented at Deep-water Circulation : Processes & Products*, Baiona (Pontevedra, Spain).

De Moustier, C., and Matsumoto, H. (1993). "Seafloor acoustic remote sensing with multibeam echo-sounders and bathymetric sidescan sonar systems." *Marine Geophysical Researches*, 15, 27-42.

Diaz-del-Rio, V., Somoza, L., Martinez-Frias, J., Mata, M., Delgado, A., Hernández-Molina, F., Lunar, R., Martin-Rubi, J., Maestro, A., Fernandez-Puga, M., Leon, R., Llave, E., Medialdea, T., and Vazquez, J. (2003). "Vast fields of hydrocarbon-derived carbonate

chimneys related to the accretionary wedge/olistostrome of the Gulf of Cadiz." *Marine Geology*, 195(1-4), 177-200.
Diez, R., Stow, D., and Hernández-Molina, F. (2008). "Sequence stratigraphy of contourite drift deposits in North Atlantic Basins.". City: http://www.cprm.gov.br/33IGC/1345431.html.
Elsow, F. (1932). "Heavy minerals as a guide in stratigraphic studies.". City: Journal of the Mineralogical Society of America, pp. 429-436.
Emery, D., and Myers, K. (1996). *Sequence Stratigraphy.*, Oxford: Blackwell.
Enjorlas, J., Gouadain, J., Mutti, E., and Pizon, J. (1986). "New turbiditic model for the Lower Tertiary sands in the South Viking Graben. ", in A. Spencer, (ed.), *Habitat of Hydrocarbons on the Norwegian Continental Shelf.* Oslo: Norwegian Petroleum Society, pp. 171-178.
EPICA Community Members. (2006). "One-to-one coupling of glacial climate variability in Greenland and Antarctica." *Nature*, 444, 195-198.
Ercilla, G., Baraza, J., Alonso, B., Estrada, F., Casas, D., and Farrán, M. (2002). "The Ceuta Drift.", in D. Stow, C. Pudsey, J. Howe, J.-C. Faugères, and A. Viana, (eds.), *Deep-water Contourite systems: modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics.* London: Geological Society, pp. 155-170.
Ercilla, G., Casas, D., Iglesias, J., Vázquez, J., Somoza, L., León, R., Medialdea, T., Juan, C., and García, M. (2010). "Contourites in the Galicia Bank region." *Geo-Temas*, 11, 33-34.
Ercilla, G., Juan, J., Estrada, F., Casas, D., Alonso, B., Garcia, M., Farran, M.-L., Maldonado, A., Team, C., and MONTERA Team. (2012). "Contourite sedimentation in the Alboran Sea: morphosedimentary characterization." *Geo-Teams*, 13, 1809-1812.
Escutia, C., Nelson, C., Acton, G., Eittreim, S., Cooper, A., Warnke, D., and Jaramillo, J. (2002). "Current controlled deposition on the Wilkes Land Continental Rise, Antarctica.", in D. Stow, C. Pudsey, J. Howe, J.-C. Faugères, and A. Viana, (eds.), *Deep-water Contourite systems: modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics.* London: Geological Society, pp. 373-384.
Essex, H., and Stow, D. (2013). "The ichnology of contourites."*International Association of Sedimentologists Annual Meeting*. City: Manchester, UK, pp. T3S4_P25.
Esteras, M., Izquierdo, J., Sandoval, N., and Bahmad, A. (2000). "Evolución morfológica y estratigráfica Plio-Cuaternaria del Umbral de Camarinal (Estrecho de Gibraltar) basada en sondeos marinos." *Revista de la Sociedad Geológica de España*, 13, 539-550.
Expedition 339 Scientists. (2012). "Site U1388 Summary."*IODP Expedition 339: Mediterranean Outflow. Site Summaries.* City: International Ocean Discovery Program: http://iodp.tamu.edu/scienceops/sitesumm/339/339_ss1388.html.
Expedition 342 Scientists. (2012). "Paleogene Newfoundland sediment drifts." *IODP Preliminary Report*, 342.
Faugères, J.-C., and Mulder, T. (2011). "Contour currents and contourite drifts", in H. Hüneke and T. Mulder, (eds.), *Deep Sea Sediments*. Developments in Sedimentology.
Faugères, J.-C., and Stow, D. (2008). "Contourite Drifts: Nature, Evolution and Controls.", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites.*: Developments in Sedimentology, pp. 259-288.
Faugères, J.-C., Zaragosi, S., and Mezerais, L. (2002a). "The Vema contourite fan in the South Brazilian basin", in D. Stow, C. Pudsey, J. Howe, J.-C. Faugères, and A. Viana, (eds.), *Deep-water contourite systems: modern drifts and ancient series, seismic and sedimentary characteristics.* London: Geological Society, pp. 209-222.
Faugères, J., Gonthier, E., and Stow, D. (1984). "Contourite drift molded by deep Mediterranean Outflow." *Geology*, 12(5), 296-300.
Faugères, J., Lima, A., Masse, L., and Zaragosi, S. (2002b). "The Columbia channel-levee system: A fan drift in the southern Brazil Basin.", in D. Stow, C. Pudsey, J. Howe, J. Faugères, and A. Viana, (eds.), *Deep-Water Contourtite Systems: Modern Drifts and Ancient*

Series, Seismic and Sedimentary Characteristics. . London: Geological Society, pp. 223-238.
Faugères, J., Mezerais, M., and Stow, D. (1993). "Contourite drifts types and their distribution in the North and South-Atlantic Ocean Basins." *Sedimentary Geology*, 82(1-4), 189-203.
Faugères, J., and Stow, D. (1993). "Bottom-current-controlled sedimentation - A synthesis of the contourite problem." *Sedimentary Geology*, 82(1-4), 287-297.
Faugères, J., Stow, D., Imbert, P., and Viana, A. (1999). "Seismic features diagnostic of contourite drifts." *MARINE GEOLOGY*, 1-38.
Fernandez-Puga, M., Vazquez, J., Somoza, L., del Rio, V., Medialdea, T., Mata, M., and Leon, R. (2007). "Gas-related morphologies and diapirism in the Gulf of Cadiz." *Geo-Marine Letters*, 27(2-4), 213-221.
Fiúza, A., Hamann, M., Ambar, I., Díaz del Río, G., González, N., and Cabanas, J. (1998). "Water masses and their circulation off western Iberia during May 1993." *Deep-Sea Research I*, 45, 1127-1160.
Flinch, J., and Vail, P. (1998). "Plio-Pleistocene sequence stratigraphy and tectonics of the Gibraltar Arc.", in P. De Graciansky, (ed.), *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins.*: SEPM (Society for Sedimentary Geology), pp. 199-208.
Folk, R. (1964). "A review of grain-size parameters." *Sedimentology*, 6, 73-93.
Folk, R., and Ward, W. (1957). "Brazos River Bar: a study in the significance of grain size parameters." *Journal of Sedimentary Petrology*, 27, 3-26.
Friedman, G., and Sanders, J. (1978). *Principles of Sedimentology.*, United States of America: John Wiley and Sons.
Fu, S., and Werner, F. (2000). "Distribution, ecology and taphonomy of the organism trace, *Scolicia*, in northeast Atlantic deep-sea sediments." *Palaeogeography, Palaeoclimatology, Palaeoecology*, 156, 289-300.
Fulthorpe, C., Lu, H., and IODP Expedition Shipboard Scientific Party. (2010). "Contourites and slope progradation: Canterbury Basin, New Zealand." *Geo-Temas*, 11.
Fütterer, D. (2006). "The solid phase of marine sediments", in H. Schulz and M. Zabel, (eds.), *Marine Geochemistry*. Germany: Springer, pp. 1-27.
Garcia-Lafuente, J., Delgado, J., Criado-Aldeanueva, F., Bruno, M., del Rio, J., and Vargas, J. (2006). "Water mass circulation on the continental shelf of the Gulf of Cadiz." *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, 53(11-13), 1182-1197.
Garcia, M., Hernández-Molina, F., Llave, E., Stow, D., Leon, R., Fernandez-Puga, M., del Rio, V., and Somoza, L. (2009). "Contourite erosive features caused by the Mediterranean Outflow Water in the Gulf of Cadiz: Quaternary tectonic and oceanographic implications." *Marine Geology*, 257(1-4), 24-40.
George, D. (2011). "TGS-Nopec's Portugal survey suspended"*Oil and Gas Online*. City.
Glaister, R., and Nelson, H. (1974). "Grain-size distributions, a aid in facies identification." *Bulletin of Canadian Petroleum Geology*, 22, 203-240.
Gong, C., Wang, Y., peng, X., Li, W., Qui, Y., and Xu, S. (2012). "Sediment waves on the South China Sea Slope off southwestern Taiwan: Implications for the intrusion of the Northern Pacific Deep Water into the South China Sea. ." *Marine and Petroleum Geology*, 32, 95-109.
Gonthier, E., Faugères, J.-C., and Stow, D. (1984). "Contourite facies of the Faro Drift, Gulf of Cadiz", in D. Stow and D. Piper, (eds.), *Fine-grained sediments: Deep-water processes and facies*. London: Geological Society, Special Publication, pp. 275-292.
Goosse, H., Campin, J.-M., and Tartinville, B. (2001). "The sources of Antarctic bottom water in a global ice-ocean model." *Ocean Model*, 3, 51-65.
Grant, J., and Schreiber, R. (1990). "Modern swathe sounding and sub-bottom profiling technology for research applications: The atlas hydrosweep and parasound systems.", in E. Hailwood and R. Kidd, (eds.), *Marine Geological Survaying and Sampling*. Netherlands: Springer, pp. 9-19.

Gröger, M., Heinrich, R., and Bickert, T. (2003). "Variability of silt grain size and planktonic foraminiferal preservation in Plio/Pleistocene sediments from the western equatorial Atlantic and Caribbean." *Marine Geology*, 201, 307-320.

Gross, M., and Gross, E. (1996). *Oceanography- A view of the Earth*.

Gutscher, M., Dominguez, S., Westbrook, G., Gente, P., Babonneau, N., Mulder, T., Gonthier, E., Bartolome, R., Luis, J., Rosas, F., Terrinha, P., and Teams, D. a. D. S. (2009). "Tectonic shortening and gravitational spreading in the Gulf of Cadiz accretionary wedge: Observations from multi-beam bathymetry and seismic profiling." *Marine and Petroleum Geology*, 26(5), 647-659.

Gutscher, M., Malod, J., Rehault, J., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., and Spakman, W. (2002). "Evidence for active subduction beneath Gibraltar." *Geology*, 30(12), 1071-1074.

Habgood, E., Kenyon, N., Masson, D., Akhmetzhanov, A., Weaver, P., Gardner, J., and Mulder, T. (2003). "Deep-water sediment wave fields, bottom current sand channels and gravity flow channel-lobe systems: Gulf of Cadiz, NE Atlantic." *Sedimentology*, 50(3), 483-510.

Hanquiez, V., Mulder, T., Lecroart, P., Gonthier, E., Marches, E., and Voisset, M. (2007). "High resolution seafloor images in the Gulf of Cadiz, Iberian margin." *Marine Geology*, 246(1), 42-59.

Hanquiez, V., Mulder, T., Toucanne, S., Lecroart, R., Bonnel, C., Marches, E., and Gonthier, E. (2010). "The sandy channel-lobe depositional systems in the Gulf of Cadiz: Gravity processes forced by contour current processes." *Sedimentary Geology*, 229(3), 110-123.

Haq, B., and Boersma, A. (1978). "Introduction to Marine Micropaleontology.". City: Elsevier Science: Netherlands, pp. 376.

Haq, B., Hardenbol, J., and Vail, P. (1987). "Chronology of fluctuating sea levels since the Triassic." *Science*, 235, 1156-1166.

Haq, B., Hardenbol, J., and Vail, P. (1988). "Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change.", in C. Wilgus, B. Hastings, C. Kendall, H. Posamentier, C. Ross, and J. Van Wagoner, (eds.), *Sea-level changes: an integrated approach.*: SEPM, pp. 72-108.

Haughton, P., and Kendall, C. (2009). "Introduction to sequence stratigraphy of deepwater clastic systems.". City: SEPM Sequence Stratigraphy Web: http://sepmstrata.org/DeepwaterClasIntro.html.

Heezen, B., and Hollister, C. (1963). "Evidence of deep-sea bottom currents from abyssal sediments"*International Association of Physical oceanography, 13th General Assembly International Union Geodesy and Geophysics*. City, pp. 111.

Hernández-Molina, F., Llave, E., Brackenridge, R., Preu, B., Ercilla, G., Fontan, A., Bruno, M., Serra, N., Stow, D., García, M., Medialdea, T., Casas, D., Juan, C., Sandoval, N., Arnaiz, A., and CONTOURIBER Team. (2013a). "Oceanographic and contourite processes associated to the Mediterranean Outflow Water after its exit from the Gibraltar Strait."*International Association of Sedimentologists, Annual Meeting 2014*. City: Manchester, UK.

Hernández-Molina, F., Llave, E., Preu, B., Ercilla, G., Fontan, A., Bruno, M., Serra, N., Gomiz, J., Brackenridge, R., Sierro, F., Stow, D., Garcia, M., Juan, C., Sandoval, N., and Arnaiz, A. (2014). "Contourite processes associated with the Mediterranean Outflow Water after its exit from the Gibraltar Strait; global and conceptual implications." *Geology*, 42, 231-234.

Hernández-Molina, F., Llave, E., Prue, B., Fontan, A., Ercilla, G., Brackenridge, R., Stow, D., Garcia, M., Medialdea, T., Sandoval, N., Casas, D., Juan, C., Bruno, A., Serra, N., and Team, C. (2013b). "Oceanographic and contourite processes associated to the Mediterranean Outflow Water after its exit from the Gibraltar Strait."*Dialogue*

Between Contourite and Oceanographic Processes: International Workshop. City: Hull, UK, pp. 34.
Hernández-Molina, F., Llave, E., and Stow, D. (2008). "Continental slope contourites", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites*. Developments in Sedimentology, pp. 379-408.
Hernández-Molina, F., Llave, E., Stow, D., Garcia, M., Somoza, L., Vazquez, J., Lobo, F., Maestro, A., del Rio, V., Leon, R., Medialdea, T., and Gardner, J. (2006). "The contourite depositional system of the Gulf of Cadiz: A sedimentary model related to the bottom current activity of the Mediterranean outflow water and its interaction with the continental margin." *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, 53(11-13), 1420-1463.
Hernández-Molina, F., Llave, E., Stow, D., Garcia, M., Somoza, L., Vazquez, J., Lobo, F., Maestro, A., del Rio, V., Leon, R., Medialdea, T., and Gardner, J. (2006). "The contourite depositional system of the Gulf of Cadiz: A sedimentary model related to the bottom current activity of the Mediterranean outflow water and its interaction with the continental margin." *Deep-Sea Research Part Ii-Topical Studies in Oceanography*, 53(11-13), 1420-1463.
Hernández-Molina, F., Paterlini, M., Somoza, L., Violante, R., Arecco, M., de Isasi, M., Rebesco, M., Uenzelmann-Neben, G., Neben, S., and Marshall, P. (2010a). "Giant mounded drifts in the Argentine Continental Margin: Origins, and global implications for the history of thermohaline circulation." *Marine and Petroleum Geology*, 27(7), 1508-1530.
Hernández-Molina, F., Paterlini, M., Violante, R., Marshall, P., de Isasi, M., Somoza, L., and Rebesco, M. (2009). "Contourite depositional system on the Argentine Slope: An exceptional record of the influence of Antarctic water masses." *Geology*, 37(6), 507-510.
Hernández-Molina, F., Serra, N., Stow, D., Llave, E., Ercilla, G., and Van Rooij, D. (2011a). "Along-slope oceanographic processes and sedimentary products around the Iberian margin." *Geo-Marine Letters*, 31(5-6), 315-341.
Hernández-Molina, F., Stow, D., Alvarez-Zarikian, C., and Expedition IODP 339 Scientists. (2013c). "IODP Expedition 339 in the Gulf of Cadiz and off West Iberia: decoding the environmental significance of the Mediterranean outflow water and its global influence."*Scientific Drilling*. City, pp. 1-11.
Hernández-Molina, F., Stow, D., and Brackenridge, R. (2010b). "Appendix IV: Surface Sediment Data Report", in F. Hernández-Molina and D. Stow, (eds.), *GUCADRILL - IODP Full Proposal*.
Hernández-Molina, F., Stow, D., Llave, E., Rebesco, M., Ercilla, G., Van Rooij, D., Mena, A., Vazquez, J.-T., and Voelker, A. (2011b). *Deep-water circulation: processes & products*: Geo-Temas.
Hernández-Molina, F., Stow, D., Llave, E., Rebesco, M., Ercilla, G., Van Rooij, D., Mena, A., Vázquez, J., and Voelker, A. "Deep-Water Circulation: Processes and Products." *Presented at Deep-Water Circulation: Processes and Products. International Congress*, Baiona, Pontevedra Spain.
Hernández-Molina, J., Llave, E., Somoza, L., Fernandez-Puga, M., Maestro, A., Leon, R., Medialdea, T., Barnolas, A., Garcia, M., del Rio, V., Fernandez-Salas, L., Vazquez, J., Lobo, F., Dias, J., Rodero, J., and Gardner, J. (2003). "Looking for clues to paleoceanographic imprints: A diagnosis of the Gulf of Cadiz contourite depositional systems." *Geology*, 31(1), 19-22.
Hernández-Molina, J., Llave, E., Somoza, L., Fernandez-Puga, M., Maestro, A., Leon, R., Medialdea, T., Barnolas, A., Garcia, M., del Rio, V., Fernandez-Salas, L., Vazquez, J., Lobo, F., Dias, J., Rodero, J., and Gardner, J. (2003). "Looking for clues to paleoceanographic imprints: A diagnosis of the Gulf of Cadiz contourite depositional systems." *Geology*, 31(1), 19-22.

Hinz, K., Neben, S., Schreckenberger, B., Roeser, H., Block, M., Goncalves de Souza, K., and Meyer, H. (1999). "The Argentine continental margin north of 48°S: sedimentary successions, volcanic activity during break-up." *Marine and Petroleum Geology*, 16.

Hohbein, M., and Cartwright, J. (2006). "3D seismic analysis of the West Shetland Drift system: Implications for Late Neogene palaeoceanography of the NE Atlantic." *Marine Geology*, 230, 1-20.

Howe, J. (1995). "Sedimentary processes and variations in slope-current activity during the last glacial-interglacial episode on the Hebrides Slope, northern Rockall Trough, North Atlantic Ocean." *Sedimentology*, 43, 219-234.

Howe, J., Stoker, M., Stow, D., and Akhurst, M. (2002). "Sediment drifts and contourite sedimentation in the northeastern Rockall Trough and Faeroe-Shetland Channel, North Atlantic Ocean.", in D. Stow, C. Pudsey, J. Howe, J.-C. Faugères, and A. Viana, (eds.), *Deep-water Contourite systems: modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics.* London: Geological Society, pp. 65-72.

Howe, M. (1982). "The Mediterranean Water Outflow in the Gulf of Cadiz." *Oceanography and Marine Biology*, 20, 37-64.

Hsü, K., Ryan, W., and Cita, M. (1973). "Late Miocene desiccation of Mediterranean." *Nature*, 242(5395), 240-244.

Hüneke, H., and Stow, D. (2008). "Identification of Ancient Contourites: Problems and Palaeoceanographic Significance", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites*. Developments in Sedimentology, pp. 323-344.

Hunt, D., and Gawthorpe, L. (2000). *Sedimentary Responses to Forced Regressions.*, London: Geological Society.

Hunter, S. (2008). *Spatial and temporal variation in contourite sedimentation; link to variations in palaeocirculation.*, University of Southampton.

Hunter, S., Wilkinson, D., Stanford, J., Stow, D., Bacon, S., Akhmetzhanov, A., and Kenyon, N. (2007). "The Eirik Drift: a long-term barometer of North Atlantic deepwater flux south of Cape Farewell, Greenland", in A. Viana and M. Rebesco, (eds.), *Economic and Palaeoceanographic Significance of Contourite Deposits*. London: Geological Society, Special Publications, pp. 245-263.

Huvenne, V., Masson, D., and Wheeler, A. (2009). "Sediment dynamics of a sandy contourite: the sedimentary context of the Darwin cold-water coral mounds, Northern Rockall Trough." *International Journal of Earth Sciences*, 98(4), 865-884.

Ito, M. (1996). "Sandy contourites of the Lower Kazusa Group in the Boso Peninsula, Japan: Kuroshio current influenced deep-sea sedimentation in a Plio-Pleistocene forearc basin. ." *Journal of Sedimentary Research*, 66, 587-598.

Janson, J., Van der Gaast, S., Koster, B., and Vaars, A. (1998). "CORTEX, a shipboard XRF-scanner for element analyses in split sediment cores." *Marine Geology*, 151, 143-153.

Juan, C., Ercilla, G., Estrada, F., Casas, D., Alonso, B., Garcia, M., Farran, M.-L., Maldonado, A., CONTOURITBER Team, and MONTERA Team. (2012). "Contourite sedimentation in the Alboran Sea: Plio-Quaternary evolution." *Geo-Temas*, 13, 1817-1820.

Kelling, G., and Stanley, D. (1972). "Sedimentary evidence of bottom current activity, Strait of Gibraltar region." *Marine Geology*, 13, 51-60.

Kenyon, N., Akhmetzhanov, A., and Ivanov, M. (2000). "Mediterranean undercurrent short study.", in N. Kenyon, M. Ivanov, A. Akhmetzhanov, and G. Akhmanov, (eds.), *Multidisciplinary Study of Geological Processes on the North Eastern Atlantic and Western Mediterranean Margins. Preliminary Results of Geological and Geophysical Investigations During the TTR-9 Cruise of R/V Professor Logachev, June-July 1999.*: UNESCO, pp. 73-75.

Kenyon, N., and Belderson, R. (1973). "Bed forms of the Mediterranean undercurrent observed with side-scan sonar." *Sedimentary Geology*, 9, 77-99.

Khelifi, N., Sarnthein, M., Andersen, N., Blanz, T., Frank, M., Garbe-Schonberg, D., Haley, B., Stumpf, R., and Weinelt, M. (2009). "A major and long-term Pliocene intensification of the Mediterranean outflow, 3.5-3.3 Ma ago." *Geology*, 37(9), 811-814.

Kinoshita, M., Tobin, H., Ashi, J., Kimura, G., Lallement, S., Screaton, E., Curewitz, D., Masago, H., Moe, K., and and the Expedition 314/315/316 Scientists. (2009). "Expedition 316 Methods." *Proceedings of the IODP 314/315/316*.

Knutz, P. (2008). "Palaeoceanographic significance of contourite drifts", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites*. Developments in Sedimentology, pp. 511-535.

Kranck, K., and Milligan, T. (1991). "Grain size in oceanography.", in J. Syvitski, (ed.), *Principles, methods, and application of particle size analysis*. Cambridge: Cambridge University Press, pp. 332-345.

Krank, K., and Milligan, T. (1991). "Grain size in oceanography.", in J. Syvitski, (ed.), *Principles, Methods, and Applications of Particle Size Analysis.* New York: Cambridge University Press, pp. 332-345.

Kuhn, G., and Weber, M. (1993). "Acoustical characterization of sediment by *Parasound* and 3.5 kHz systems: Related sedimentary processes on the southeastern Weddell Sea continental slope, Antarctica." *Marine Geology*, 113(3-4), 201-217.

Laberg, J., and Camerlenghi, A. (2008). "The Significance of Contourites for Submarine Slope Stability", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites*. Developments in Sedimentology, pp. 537-556.

Laberg, J., Stoker, M., Dahlgren, K., de Haas, H., Haflidason, H., Hjelstuen, B., Nielsen, T., Shannon, P., Vorren, T., van Weering, T., and Ceramicola, S. (2005). "Ceaozoic alongslope processes and sedimentation on the NW European Atlantic margin." *Marine and Petroleum Geology*, 22(9-10), 1069-1088.

Laberg, J., and Vorren, T. (2004). "Weichselian and Holocene growth of the northern high-latitude Lofoten Contouritre Drift on the continental slope of Norway." *Sedimentary Geology*, 164, 1-17.

Laberg, J. S., Dahlgren, T., Vorren, T., Haflidason, H., and Bryn, P. (2001). "Seismic analyses of Cenozoic contourite drift development in the Northern Norwegian Sea." *Marine Geophysical Researches*, 22, 401-416.

Leeder, M. (1999). *Sedimentology and Sedimentary Basins: From Turbulence to Tectonics.*, Oxford: Blackwell.

Legg, S., Briegleb, B., Chang, Y., Chassignet, E., Danabasoglu, G., Ezer, T., Gordon, A., Griffies, S., Hallberg, R., Jackson, L., and Large, W. (2009). "Improving oceanic overflow representation in climate models. The gravity current entrainment climate process team." *Bulletin of the American Meteorological Society*, 90, 657-670.

Lewis, D., and McConchie, D. (1994). *Analytical Sedimentology.*, New York: Chapman & Hall.

Llave, E., Heránndez-Molina, F., Brackenridge, R., and Stow, D. "Pliocene and Quaternary sandy deposits along the proximal and middle sectors of the Gulf of Cádiz contourite depositional system: preliminary results." *Presented at IODP Expedition 339: 2nd Post-Cruise Meeting*, Tarifa, Spain.

Llave, E., Heránndez-Molina, F., Somoza, L., Stow, D., and Díaz Del Río, V. (2007a). "Quaternary evolution of the depositional system in the Gulf of Cadiz.", in A. Viana and M. Rebesco, (eds.), *Economic and Palaeoceanographic Significance of Contourite Deposits*. London: Geological Society, pp. 49-79.

Llave, E., Hernández-Moliana, F., Stow, D., Fernández-Puga, M., García, M., Vázquez, J., Maestro, A., Somoza, L., and Díaz del Río, V. (2007b). "Reconstructions of the Mediterranean Outflow Water during the Quaternary based on the study of changes in buried mounded drift stacking pattern in the Gulf of Cadiz." *Marine Geophysical Research*, 28, 379-394.

Llave, E., Hernández-Molina, F., Ercilla, G., Garcia, M., Roque, C., Van Rooij, D., Stow, D., Juan, C., Brackenridge, R., Jane, G., and Mena, A. (*In Press*). "Water masses circulation processes along the Iberian Continental Margin", *Monographic Special Volume*. IGME.

Llave, E., Hernández-Molina, F., Somoza, L., Diaz-del-Rio, V., Stow, D., Maestro, A., and Dias, J. (2001). "Seismic stacking pattern of the Faro-Albufeira contourite system (Gulf of Cadiz): a Quaternary record of paleoceanographic and tectonic influences." *Marine Geophysical Researches*, 22(5-6), 487-508.

Llave, E., Hernández-Molina, F., Stow, D., Fernandez-Puga, M., Garcia, M., Vasquez, J., Maestro, A., Somaza, L., and Del Rio, V. (2007c). "Reconstructions of the Mediterranean Outflow Water during the quaternary based on the study of changes in buried mounded drift stacking pattern in the Gulf of Cadiz." *Marine Geophysical Researches*, 28(4), 379-394.

Llave, E., Matias, H., Hernández-Molina, F., Ercilla, G., Stow, D., and Medialdea, T. (2011). "Pliocene-Quaternary contourites along the northern Gulf of Cadiz margin: sedimentary stacking pattern and regional distribution." *Geo-Marine Letters*, 31(5-6), 377-390.

Llave, E., Matias, H., Hernández-Molina, F., Ercilla, G., Stow, D., and Medialdea, T. (2010). "Pliocene and Quaternary seismic stacking pattern and distribution of contourites in the Algarve margin (Northern Gulf of Cadiz, Spain)." *Geo-Temas*, 11, 103-104.

Llave, E., Schonfeld, J., Hernández-Molina, F., Mulder, T., Somoza, L., del Rio, V., and Sanchez-Almazo, I. (2006). "High-resolution stratigraphy of the Mediterranean outflow contourite system in the Gulf of Cadiz during the late Pleistocene: The impact of Heinrich events." *Marine Geology*, 227(3-4), 241-262.

Lobo, F., Hernández-Molina, F., Somoza, L., Rodero, J., Maldonado, A., and Barnolas, A. (2000). "Patterns of bottom current flow deduced from dune asymmetries over the Gulf of Cadiz shelf (southwest Spain)." *Marine Geology*, 164(3-4), 91-117.

Lobo, F., Maldonado, A., and Noormets, R. (2010). "Large-scale sediment bodies and superimposed bedforms on the continental shelf close to the Strait of Gibraltar: interplay of complex oceanographic conditions and physiographic constraints." *Earth Surface Processes and Landforms*, 35(6), 663-679.

Lobo, F., and Ridente, D. (2014). "Stratigraphic architecture and spatio-temporal variability of high-frequency (Milankovitch) depositional cycles on modern continental margins: An overview." *Marine Geology* In Press.

Lopes, F., Cunha, P., and Le Gall, B. (2006). "Cenozoic seismic stratigraphy and tectonic evolution of the Algarve margin (offshore Portugal, southwestern Iberian Peninsula)." *Marine Geology*, 231(1-4), 1-36.

Lovell, J., and Stow, D. (1981). "Identification of ancient sandy contourites." *Geology*, 9, 347-349.

Lowe, J., and Walker, M. (1997). *Reconstructing Quaternary Environments*, London: Pearson International.

Löwemark, L., Schönfeld, J., Werner, F., and Schäfer, P. (2004). "Trace fossils as a paleoceanographic tool: Evidence from Late Quaternary sediments of the southwestern Iberian margin." *Marine Geology*, 204, 27-41.

Lynch-Stieglitz, L., Adkins, J., Curry, W., Dokken, T., Hall, I., Herguera, J., Hirschi, J.-M., Ivanova, E., Kissel, C., Marchal, O., Marchitto, T., McCave, N., McManus, J., Mulitza, S., Ninnemann, U., Peeters, F., Yu, E.-F., and Zahn, R. (2007). "Atlantic meridional overturning circulation during the last glacial maximum." *Science*, 316, 66-69.

MacEachern, J., Raychaudhuri, I., and Pemberton, S. (1992). "Stratigraphic applications of the glossifungites ichnofacies: delineating discontinuities in the rock record.", in S. Pemberton, (ed.), *Applications of Ichnology to Petroleum Exploration*. Society for Sedimentary Geology, pp. 169-198.

Madelain, F. (1970). "Influence de la topographie du fond sur l'ecoulement méditerranéen entre le Detroit de Gibraltar et le Cap Saint-Vincent." *Cashiers Océanographiques*, 22, 43-61.

Magoon, L., and Beaumont, E. (2003). "Petroleum Systems." *AAPG Search and Discovery*, Article #40068

Maldonado, A., Barnolas, A., Bohoyo, F., Galindo-Zaldivar, J., Hernández-Molina, J., Lobo, F., Rodriguez-Fernandez, J., Somoza, L., and Vazquez, J. (2003). "Contourite deposits in the central Scotia sea: the importance of the Antarctic Circumpolar Current and the Weddell Gyre Flows." *Palaeogeography Palaeoclimatology Palaeoecology*, 198(1-2), 187-221.

Maldonado, A., and Nelson, C. (1999a). "Interaction of tectonic and depositional processes that control the evolution of the Iberian Gulf of Cadiz margin." *Marine Geology*, 155(1-2), 217-242.

Maldonado, A., and Nelson, C. H. (1999b). "Interaction of tectonic and depositional processes that control the evolution of the Iberian Gulf of Cadiz margin." *Marine Geology*, 155(1-2), 217-242.

Maldonado, A., Somoza, L., and Pallares, L. (1999). "The Betic orogen and the Iberian-African boundary in the Gulf of Cadiz: geological evolution (central North Atlantic)." *Marine Geology*, 155(1-2), 9-43.

Malvern Instruments Limited. (2012). "A Basic Guide to Particle Characterization.". City.

Marches, E., Mulder, T., Cremer, M., Bonnel, C., Hanquiez, V., Gonthier, E., and Lecroart, P. (2007). "Contourite drift construction influenced by capture of Mediterranean Outflow Water deep-sea current by the Portimao submarine canyon (Gulf of Cadiz, South Portugal)." *Marine Geology*, 242(4), 247-260.

Marches, E., Mulder, T., Gonthier, E., Cremer, M., Hanquiez, V., Garlan, T., and Lecroart, R. (2010). "Perched lobe formation in the Gulf of Cadiz: Interactions between gravity processes and contour currents (Algarve Margin, Southern Portugal)." *Sedimentary Geology*, 229(3), 81-94.

Martín-Chivelet, J., Fregenal-Martínez, M., and Chacón, B. (2008). "Traction structures in contourites.", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites*. Amsterdam: Developments in Sedimentology, pp. 159-182.

Martins, L. (1965). "Significance of skewness and kurtosis in environmental interpretation." *Journal of Sedimentary Research*, 35, 768-770.

Martins, L. (2003). "Recent sediments and grain-size analysis." *Gravel*, 1, 90-105.

Mason, C., and Folk, R. (1958). "Differentiation of beach, dune, and aeolian flat environments by size analysis, Mustang Island, Texas." *Journal of Sedimentary Petrology*, 28, 211-226.

Masson, D. G., Plets, R. M. K., Huvenne, V. A. I., Wynn, R. B., and Bett, B. J. (2010). "Sedimentology and depositional history of Holocene sandy contourites on the lower slope of the Faroe-Shetland Channel, northwest of the UK." *MARINE GEOLOGY*, 268(1-4), 85-96.

McCaffrey, W., and Kneller, B. (2001). "Process controls on the development of stratigraphic trap potential on the margins of confined turbidite systems and aids to reservoir evaluation." *Aapg Bulletin*, 85(6), 971-988.

McCave, I. (1984). "Erosion, transport and deposition of fine-grained marine sediments.", in D. Stow and D. Piper, (eds.), *Fine-Grained Sediments: Deep-Water Processes and Facies.* London: Geological Society, pp. 35-69.

McCave, I. (2008). "Size sorting during transport and deposition of fine sediments: sortable silt and flow speed.", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites*. Developments in Sedimentology, pp. 121-142.

McCave, I., Bryant, R., Cook, H., and Coughanowr, C. (1986). "Evaluation of a laser-diffraction-size analyzer for use with natural sediments." *Journal of Sedimentary Petrology*, 56, 561-564.

McCave, I., Manighetti, B., and Beveridge, N. (1995). "Circulation in the glacial North Atlantic inferred from grain-size measurements." *Nature*, 374, 149-152.

McCave, I., and Syvitski, J. (1991). "Principles and methods of geological particle size analysis", in J. Syvitski, (ed.), *Principles, Methods, and Application of Particle Size Analysis.* New York: Cambridge University Press, pp. 3-21.

McCave, I., and Tucholke, B. (1986). "Deep current-controlled sedimentation in the western North Atlantic", in P. Vogt and B. Tucholke, (eds.), *The Geology of North America, the Western North Atlantic Region, Decade of North American Geology*. Boulder: Geological Society of America, pp. 451-468.

McLennan, S., Hemming, S., McDaniel, D., and Hanson, G. (1993). "Geochemical approaches to sedimentation, provenance, and tectonics." *Geological Society of America, Special Paper*, 243, 21-40.

Medialdea, T., Somaza, L., León, R., Farrán, M., Ercilla, G., Maestro, a., Casas, D., Llave, E., Hernández-Molina, J., Fernández-Puga, M., and Alonso, B. (2008). "Multibeam backscatter as a tool for sea-floor characterization and identification of oil spills in the Galicia Bank." *Marine Geology*, 249(1-2), 93-107.

Medialdea, T., Somoza, L., Pinheiro, L., Fernandez-Puga, M., Vazquez, J., Leon, R., Ivanov, M., Magalhaes, V., Diaz-del-Rio, V., and Vegas, R. (2009). "Tectonics and mud volcano development in the Gulf of Cadiz." *Marine Geology*, 261(1-4), 48-63.

Medialdea, T., Vegas, R., Somoza, L., Vazquez, J., Maldonado, A., Diaz-Del-Rio, V., Maestro, A., Cordoba, D., and Fernandez-Puga, M. (2004). "Structure and evolution of the "Olistostrome" complex of the Gibraltar Arc in the Gulf of Cadiz (eastern Central Atlantic): evidence from two long seismic cross-sections." *Marine Geology*, 209(1-4), 173-+.

Mees, F., Swennen, R., Van Geet, M., and Jacobs, P. (2003). "Applications of X-ray computer tomography in the geosciences.", in F. Mees, R. Swennen, M. Van Geet, and P. Jacobs, (eds.), *Applications of X-ray Computer Tomography in the Geosciences.* London: Geological Society, pp. 1-6.

Mienert J., Vanneste M Bünz S., Andreassen, K., Haflidason H., Sejrup, H.P. (2005) “Ocean warming and gas hydrate stability on the mid-Norwegian margin and the Storegga Slide.”, *Marine and Petroelum Geology,* 22, 233-244.

Melières, F. (1974). Researchs sur la dynamique sédimentuire *du Golfe de Cádiz (Espagne).* University of Paris.

Mena, A., Aguiar, P., Barreiro, J., Francés, G., and Pérez-Arlucea, M. (2011). "The use of CT-scan as sedimentary methodology: stratigraphy and sedimentary processes of Interior Galicia Basin as an example."*28th IAS Meeting of Sedimentology*. City: Zaragoza, Spain, pp. 303.

Mena, A., Francés, G., Pérez-Arlucea, M., Hanebuth, T., and Nombela, M. (2010). "Sedimentary evolution of the Galicia Inner Basin during the last 70 kyr." *Geo-Temas*, 11, 125-126.

Mézarais, M., Faugères, J., Figueiredo, A., and Massé, L. (1993). "Contour current accumulation off Vema Channel mouth, Southern Brazil Basin." *Sedimentary Geology* 82, 173-188.

Michels, K., Kuhn, G., Hillenbrand, C., Diekmann, B., Futterer, D., Grobe, H., and Uenzelmann-Neben, G. (2002). "The southern Weddell Sea: Combined contourite-turbidite sedimentation at the southeastern margin of the Weddell Gyre", in D. Stow, C. Pudsey, J. Howe, J. Faugères, and A. Viana, (eds.), *Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics.* . London: Geological Society, pp. 305-324.

Miller, K., Kominz, M., Browning, J., Wright, J., Mountain, G., Katz, M., Sugarman, P., Cramer, B., Christie-Blick, N., and Pekar, S. (2005). "The phanerozoic record of global sea-level change." *Science*, 310(5752), 1293-1298.

Millot, C. (1999). "Circulation in the Western Mediterranean Sea outflow." *Progress in Oceanography*, 82, 101-124.

Millot, C. (2009). "Another description of the Mediterranean Sea outflow." *Progress in Oceanography*, 82(2), 101-124.

Mitchum, R., Vail, P., and Sangree, J. (1977). "Seismic stratigraphy and global changes of sea-level. Part 6: Stratigraphic interpretation of seismic reflection patterns in depositional sequences.", in C. Payton, (ed.), *Seismic stratigraphy - applications to hydrocarbon exploration.*: AAPG, pp. 117-133.

Moraes, M., Maciel, W., Braga, M., and Viana, A. (2007). "Bottom-current reworked Palaeocene-Eocene deep-water reservoirs of the Campos Basin, Brazil.", in A. Viana and M. Rebesco, (eds.), *Economic and Palaeoceanographic Significance of Contourite Deposits.* London: Geological Society, Special Publications, pp. 81-94.

Mougenot, D., and Vanney, J. (1982). "Les rides de contourites Plio-Quaternaires de la pente continentale sud-portugaise." *Bulletin Institut Géologie Bassin d'Aquitaine*, 31, 131-139.

Mulder, T., Faugères, J.-C., and Gonthier, E. (2008). "Mixed turbidite-contourite systems.", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites.* . Developments in Sedimentology, pp. 435-456.

Mulder, T., Gonthier, E., Lecroart, P., Hanquiez, V., Marches, E., and Voisset, M. (2009). "Sediment failures and flows in the Gulf of Cadiz (eastern Atlantic)." *Marine and Petroleum Geology*, 26(5), 660-672.

Mulder, T., Lecroart, P., Hanquiez, V., Marches, E., Gonthier, E., Guedes, J., Thiebot, E., Jaaidi, B., Kenyon, N., Voisset, M., Perez, C., Sayago, M., Fuchey, Y., and Bujan, S. (2006). "The western part of the Gulf of Cadiz: contour currents and turbidity currents interactions." *Geo-Marine Letters*, 26(1), 31-41.

Mulder, T., Voisset, M., Lecroart, P., Le Drezen, E., Gonthier, E., Hanquiez, V., Faugères, J., Habgood, E., Hernández-Molina, F., Estrada, F., Llave-Barranco, E., Poirier, D., Gorini, C., Fuchey, Y., Voelker, A., Freitas, P., Sanchez, F., Fernandez, L., Kenyon, N., and Morel, J. (2003). "The Gulf of Cadiz: an unstable giant contouritic levee." *Geo-Marine Letters*, 23(1), 7-18.

Mutti, E., Barros, M., Possato, S., and Rumenos, L. (1980). "Deepsea fan turbidite sediments winnowed by bottom currents in the Eocene of the Campos Basin, Brazilian offshore."*IAS First European Regional Meeting*. City: International Association of Sedimentologist, pp. 114.

Mutti, E., and Carminatti, M. (2012). "Deep-water sands of the Brazilian offshore basins." *AAPG Search and Discovery*, Article #30219.

Myers, K., and Milton, N. (1996). "Concepts and principles.", in D. Emery and K. Myers, (eds.), *Sequence stratigraphy.* Oxford: Blackwell.

Negre, C., Zahn, R., Thomas, A., Masqué, P., Henderson, G., Martinez-Méndez, G., Hall, I., and Mas, J. (2010). "Reversed flow of Antarctic deep water during the Last Glacial Maximum." *Nature*, 468, 84-87.

Nelson, C., Baraza, J., and Maldonaldo, A. (1993). "Mediterranean Undercurrent Sandy Contourites, Gulf of Cadiz, Spain." *Sedimentary Geology*, 82(1-4), 103-131.

Nelson, C., and Maldonado, A. (1999). "The Cadiz margin study off Spain: an introduction." *Marine Geology*, 155(1-2), 3-8.

Nelson, C. H., Baraza, J., Maldonado, A., Rodero, J., Escutia, C., and Barber Jr, J. H. (1999). "Influence of the Atlantic inflow and Mediterranean outflow currents on Late Quaternary sedimentary facies of the Gulf of Cadiz continental margin." *Marine Geology*, 155(1-2), 99-129.

Newman, L. (2007). "GPH 111 - Introduction to Physical Geography. Fluvial Processes: Supplemental Lecture Materials". City: http://web.gccaz.edu/~lnewman/gph111/topic_units/fluvial/fluvial2.html.

Nichols, G. (2009). *Sedimentology and Stratigraphy: Second Edition.*, Oxford: Wiley-Blackwell.

Nielsen, J. (1912). *Hydrography of the Mediterranean and adjacent waters*, Copenhagen.

Nielsen, T., Andersen, C., Knutz, P., and Kuijpers, A. (2011). "The Middle Miocene to Recent Davis Strait Drift Complex: implications for Arctic–Atlantic water exchange." *Geo-Marine Letters*, 31, 419-426.

Nielsen, T., Kuijpers, A., and Knutz, P. (2008). "Seismic expression of contourite depositional systems", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites*. Developments in Sedimentology, pp. 301-322.

NOAA, N. O. a. A. A. (n.d.). "Fingerprints of Emissions and the Carbon Cycle: Stable and Radiocarbon Isotopes of Carbon Dioxide.". City, pp. http://www.esrl.noaa.gov/gmd/outreach/isotopes/decay.html.

Odonnell, R., Thierens, M., Murray-Wallace, C., Dorschel, B., and Wheeler, A. (2007). "IODP Expedition 307: A high resolution record of contourite deposition and palaeoclimatic forcing on the Eastern Porcupine Seabright (Irish Continental Margin)"*American Geophysical Union, Fall Meeting*. City: San Francisco, pp. #B31C-0509.

Ogg, J., and Ogg, G. (2008). "Neogene-Late Oligocene (0-33 Ma time-slice).". City: Subcommission for Stratigraphic Information.: http://stratigraphy.science.purdue.edu/charts/educational.html.

Orsi, A., Johnson, G., and Bullister, J. (1999). "Circulation mixing and production of Antarctic Bottom Water." *Progress in Oceanography*, 43, 55-109.

Orsi, T., Edwards, C., and Anderson, A. (1994). "X-ray computed tomography: A nondestructive method for quantitative analysis of sediment cores." *Journal of Sedimentary Research*, 64, 690-693.

Ovrebo, L., Haughton, P., and Shannon, P. (2006). "A record of fluctuating bottom currents on the slopes west of the Porcupine Bank, offshore Ireland - implications for Late Quaternary climate forcing." *Marine Geology*, 225(1-4), 279-309.

Pettijohn, F., Potter, P., and Siever, R. (1987). *Sand and Sandstone.*, New York: Springer-Verlag.

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

Piotrowski, A., Goldstein, S., Hemming, S., and Fairbanks, R. (2004). "Intensification and variability of ocean circulation through the last deglaciation." *Earth and Planetary Science Letters*, 225, 205-220.

Posamentier, H., and James, D. (2009). "An overview of sequence stratigraphic concepts: uses and abuses.", in H. Posamentier, C. Summerhayes, B. Haq, and G. Allen, (eds.), *Sequence Stratigraphy and Facies Associations.* Oxford: Blackwell.

Posamentier, H., Jervey, M., and Vail, P. (1988). "Eustatic controls on clastic deposition I - conceptual framework.", in C. Wilgus, B. Hastings, C. Kendall, H. Posamentier, C. Ross, and J. Van Wagonar, (eds.), *Sea-level Changes: an Integrated Approach.*: SEPM, pp. 110-124.

Posamentier, H., and Vail, P. (1988). "Eustatic controls on clastic deposition II - sequence and systems tracts models.", in C. Wilgu, B. Hastings, C. Kendall, H. Posamentier, C. Ross, and J. Van Wagoner, (eds.), *Sea-level Changes: an Integrated Approach.*: SEPM, pp. 125-154.

Powell, R., and Cooper, J. (2002). "A glacial sequence stratigraphic model for temperate, glaciated continental shelves.", in J. Dowdeswell and C. Ó Cofaigh, (eds.), *Glacier-Influenced Sedimentation on High-Latitude Continental Margins.* London: Geological Society, pp. 215-244.

Rahmstorf, S. (2002). "Ocean circulation and climate during the past 120,000 years." *Nature*, 419, 207-214.

Rahmstorf, S. (2006). "Thermohaline ocean circulation", in S. Elias, (ed.), *Encyclopedia of Quaternary Sciences*. Amsterdam: Elsevier, pp. 1-10.

Rasmussen, S., and Surlyk, F. (2012). "Facies and ichnology of an Upper Cretaceous chalk contourite drift complex, eastern Denmark, and the validity of contourite facies models." *Journal of the Geological Society*, 169(4), 435-447.

Reading, H., and Levell, B. (1996). *Sedimentary environments: processes, facies, and stratigraphy*, Oxford: Blackwell Science.

Rebesco, M. (2005). "Contourites", in R. Selley, L. Cocks, and I. Plimer, (eds.), *Encyclopedia of Geology*. Oxford: Elsevier, pp. 513-527.

Rebesco, M., and Camerlenghi, A. (2008). *Contourites*, Amsterdam: Developments in Sedimentology.

Rebesco, M., Hernádez-Molina, F., Van Rooij, D., and Wåhlin, A. (2014). "Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations." *Marine Geology*, In Press.

Rebesco, M., Larter, R., Barker, P., Camerlenghi, A., and Vanneste. (1997). "The history of sedimentation on the continental rise west of the Antarctic Peninsula.", in P. Barker and A. Cooper, (eds.), *Geology and Seimsic Stratigraphy of the Antarctic Margin, Part 2.*, pp. 29-49.

Rebesco, M., Pudsey, C., Canals, M., Camerlenghi, A., Baker, P., Estrada, F., and Giorgetti, A. (2002). "Sediment drifts and deep-sea channel systems, Antarctic Peninsula Pacific Margin.", in D. Stow, C. Pudsey, J. Howe, J.-C. Faugères, and V. AR, (eds.), *Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics.* London: Geological Society, pp. 353-371.

Rebesco, M., and Stow, D. (2001). "Seismic Expression on Contourites and Related Deposits: A Preface." *Marine Geophysical Research*, 22, 303-308.

Riaza, C., and Marínez Del Olmo, W. (1996). "Depositional model of the Guadalquivir-Gulf of Cadiz Tertiary Basin", in P. Friend and C. Dabrio, (eds.), *Tertiary Basins of Spain: The Stratigraphic Record of Crustal Kinematics*. Cambridge: Cambridge University Press, pp. 330-338.

Richter, T., Van der Gaast, S., Koster, B., Vaars, A., Gieles, R., De Stigter, H., De Haas, H., and Van Weering, T. (2006). "The Avaatech XRF Core Scanner: technical description and applications to NE Atlantic sediments.", in R. Rothwell, (ed.), *New Techniques in Sediment Core Analysis*. London: Geological Society, pp. 39-50.

Roberts, D. (1970). "The Rift-Betic orogen in the Gulf of Cadiz." *Marine Geology*, 9, M31-37.

Robinson, S., and McCave, I. (1994). "Orbital forcing of bottom-current enhanced sedimentation on Feni Drift, NE Atlantic, during the Mid Pleistocene." *Paleoceanography*, 9(6), 943-972.

Roest, W., and Srivastava, S. (1991). "Kinematics of the plate boundaries between Eurasia, Iberia, and Africa in the North Atlantic from the Late Cretaceous to present." *Geology*, 19(6), 613-616.

Rogerson, M., Legg, S., Van Rooij, D., Brackenridge, R., Preu, B., Stow, D., and Hernández-Molina, F. "Dialogue Between Contourite and Oceanography Processes. International Workshop.", University of Hull, UK.

Rogerson, M., Rohling, E., Bigg, G., and Ramirez, J. (2012). "Paleoceanography of the Atlantic-Mediterranean exchange: overview and first quantitative assessment of climate forcing." *Reviews of Geophysics*, 50.

Rogerson, M., Rohling, E., Weaver, P., and Murray, J. (2005). "Glacial to interglacial changes in the settling depth of the Mediterranean Outflow plume." *Paleoceanography*, 20(3).

Rogerson, M., Schonfeld, J., and Leng, M. (2011). "Qualitative and quantitative approaches in palaeohydrography: A case study from core-top parameters in the Gulf of Cadiz." *Marine Geology*, 280(1-4), 150-167.

Röhl, U. "XRF Core Scanning." *Presented at ECORD Summerschool on 'Dynamics of Past Climate Changes'*, Bremen.

Rohling, E., and Zachariasse, W. (1999). "Red Sea outflow during the last glacial maximum." *Quaternary International*, 31, 77-83.

Roque, A. (2007). *Tectonostratigrafia do cenozóico das margens continentais sul e sudoeste portuguesas: um modelo de correlação sismostratigráfica.*, Universidade de Lisboa, Portugal.

Roque, C., Duarte, H., Terrinha, P., Valadares, V., Noiva, J., Cachao, M., Ferreira, J., Legoinha, P., and Zitellini, N. (2012). "Pliocene and Quaternary depositional model of the Algarve margin contourite drifts (Gulf of Cadiz, SW Iberia): Seismic architecture, tectonic control and paleoceanographic insights." *Marine Geology*, 303, 42-62.

Rosenbaum, G., Lister, G., and Duboz, C. (2002). "Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene.", in G. Rosenbaum and G. Lister,

(eds.), *Reconstruction of the evolution of the Alpine-Himalayan orogen.*: Journal of the Virtual Explorer, pp. Paper 6.
Rothwell, R. (1989). *Minerals and Mineraloids in Marine Sediments: An Optical Guide.*, Barking, England: Elsevier Applied Science.
Rothwell, R., and Rack, F. (2006). "New techniques in sediment core analysis: an introduction", in R. Rothwell, (ed.), *New Techniques in Sediment Core Analysis*. London: Geological Society, pp. 1-29.
Roveri, M., Flecker, R., Krijgsman, W., Lofi, J., Lugli, S., Manzi, V., Sierro, F., Bertini, A., Camerlenghi, A., De Lange, G., Govers, R., Hilgen, F., Hübscher, C., Meijer, P., and Stoica, M. (2014). "The Messinian Salinity Crisis: Past and future of a great challenge for marine sciences." *Marine Geology*, in press.
Savoye, B., Piper, D., and Droz, L. (1993). "Plio-Pleistocene evolution of the Var deep-sea fan off the French Riviera." *Marine and Petroleum Geology*, 10, 550-571.
Schlager, W. (2005). *Carbonate sedimentology and sequence stratigraphy.*: SEPM.
Schlitzer, R. (2013). "Ocean Data View". City: http://odv.awi.de.
Schmiedl, G., Kuhnt, T., Ehrmann, W., Emis, K.-C., Hamann, Y., Kotthoff, U., Dulski, P., and Pross, J. (2010). "Climatic forcing of eastern Mediterranean deep-water formation and benthic ecosystems during the past 22,000." *Quaternary Science Reviews*, 29, 23-24.
Schmittner, A. (2003). "Southern Ocean sea ice and radiocarbon ages of glacial bottom waters." *Earth and Planetary Science Letters*, 213, 53-62.
Schultz, K., and Zeebe, R. (2006). "Pleistocene glacial terminations triggered by synchronous changes in Southern and Northern Hemisphere insolation: The insolation canon hypothesis." *Earth and Planetary Science Letters*, 249, 326-336.
Schönfeld, 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.
Serra, N., Ambar, I., and Boutov, D. (2010). "Surface expression of Mediterranean Water dipoles and their contribution to the shelf/slope - open ocean exchange." *Ocean Science*, 6, 191-209.
Shackley, M. (2011). "An introduction to X-Ray Fluorescence (XRF) analysis in Archaeology", in M. Shackley, (ed.), *X-Ray Fluorescence Spectrometry (XRF) in Geoarchaeology*. New York: Springer, pp. 7-44.
Shanmugam, G. (2003). "Deep-marine tidal bottom currents and their reworked sands in modern and ancient submarine canyons." *Marine and Petroleum Geology*, 20(5), 471-491.
Shanmugam, G. (2006). "Deep-water bottom currents." *Handbook of Petroleum Exploration and Production*, 5, 85-139.
Shanmugam, G. (2012a). "Discussion of He et al. (2001, Geo-Marine Letters) evidence of internal-wave and internal-tide deposits in the Middle Ordovician Xujiajuan Formation of the Xiangshan Group, Ningxia, China." *Geo-Marine Letters*, 32, 359-366.
Shanmugam, G. (2012b). *New Perspectives on Deep-Water Sandstones: Origin Recognition, Initiation, and Reservoir Quality.*, Oxford: Elsevier.
Shanmugam, G., and Moiola, R. (1982). "Eustatic control of deep-sea reservoir facies." *Aapg Bulletin-American Association of Petroleum Geologists*, 66(5), 629-629.
Shanmugam, G., Spalding, T., and Rofheart, D. (1995). "Deep-marine bottom-current reworked sand (Pliocene and Pleistocene), Ewing Bank 826 Field, Gulf of Mexico", *SEPM Core Workshop No.20, Turbidites and associated deep-water facies*. Houston, pp. 25-54.
Shannon, P., Stoker, M., Praeg, D., van Weering, T., de Haas, H., Nielsen, T., Dahlgren, K., and Hjelstuen, B. (2005). "Sequence stratigraphic analysis in deep-water, underfilled NW European passive margin basins." *Marine and Petroleum Geology*, 22(9-10), 1185-1200.

Shao, L., Li, X., Geng, J., Pang, X., Lei, Y., Qiao, P., Wang, L., and Wang, H. (2007). "Deep water bottom current deposition in the northern South China Sea." *Science in China Series D Earth Sciences*, 50(7), 1060-1006.

Shepard, F., and Young, R. (1961). "Distinguishing between beach and dune sands." *Journal of Sedimentary Petrology*, 31, 196-214.

Sierro, F. J., Flores, J. A., and Baraza, J. (1999). "Late glacial to recent paleoenvironmental changes in the Gulf of Cadiz and formation of sandy contourite layers." *Marine Geology*, 155(1-2), 157-172.

Somoza, L., Diaz-del-Rio, V., Leon, R., Ivanov, M., Fernandez-Puga, M., Gardner, J., Hernández-Molina, F., Pinheiro, L., Rodero, J., Lobato, A., Maestro, A., Vazquez, J., Medialdea, T., and Fernandez-Salas, L. (2003). "Seabed morphology and hydrocarbon seepage in the Gulf of Cadiz mud volcano area: Acoustic imagery, multibeam and ultra-high resolution seismic data." *Marine Geology*, 195(1-4), 153-176.

Srivastava, S., Schouten, H., Roest, W., Klitgord, K., Kovacs, L., Verhoef, J., and Macnab, R. (1990). "Iberian plate kinematics - a jumping plate boundary between Eurasia and Africa." *Nature*, 344(6268), 756-759.

Stanley, D. (1993). "Model for turbidite-to-contourite continuum and multiple process transport in deep marine settings: examples in the rock record." *Sedimentary Geology*, 82, 241-255.

Stanley, V. (2011). "TMI; Tool for Microscope Identification.", U. o. Minnesota, (ed.). City: https://tmi.laccore.umn.edu/.

Steig, E. (2006). "The north-south connection." *Nature*, 444, 152-153.

Stoker, M., Akhurst, M., Howe, J., and Stow, D. (1998). "Sediment drifts and contourites on the continental margin off northwest Britain." *Sedimentary Geology*, 115(1-4), 33-51.

Stoker, M., Pheasant, J., and Josenhams, H. (1997). "Seismic Methods and Interpretation.", in T. Davies, T. Bell, A. Cooper, H. Josenhans, L. Polyak, A. Solheim, M. Stoker, and J. Stravers, (eds.), *Glaciated Continental Margins: An Atlas of Acoustic Images*. Netherlands: Springer, pp. 9-26.

Stow, D., Armishaw, J., and Holmes, R. (2002a). "Holocene contourite sand sheet on the Barra Fan slope, NW Hebridean margin.", in D. Stow, C. Pudsey, J. Howe, J.-C. Faugères, and A. Viana, (eds.), *Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics.* London: Geological Society, pp. 99-120.

Stow, D., Brackenridge, R., and Hernández-Molina, F. (2011a). "Contourite sheet sands: new deepwater exploration target."*AAPG Annual Conference and Exhibition*. City: Houston, USA.

Stow, D., Brackenridge, R., Patel, U., and Toulmin, S. (2012). "Geohazards and Ocean Hazards in Deepwater: Overview and methods of Assessment"*Offshore Technology Conference*. City: Houston, Texas, pp. 23697-PP.

Stow, D., and Faugères, J.-C. (2008). "Contourite facies and faces model.", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites.*: Developments in Sedimentology, pp. 223-250.

Stow, D., Faugères, J.-C., and Gonthier, E. (1986). "Facies distribution and textural variation in Faro Drift contourites: Velocity fluctuation and drift growth." *Marine Geology*, 72, 71-100.

Stow, D., Faugères, J.-C., Gonthier, E., Cremer, M., Llave, E., Hernández-Molina, F., Somoza, L., and Díaz-Del-Río, V. (2002b). "Faro-Albufeira drift complex, northern Gulf of Cadiz". City: Geological Society , London , Memoirs, pp. 137-154.

Stow, D., Faugères, J.-C., Howe, J., Pudsey, C., and Viana, A. (2002c). "Bottom currents, contourites and deep-sea sediment drifts: current state-of-the-art", in D. Stow, C. Pudsey, J. Howe, J.-C. Faugères, and A. Viana, (eds.), *Deep-water contourite systems: modern drifts and ancient series, seismic and sedimentary characteristics*. London: Geological Society, Memoirs, pp. 7-20.

Stow, D., and Faugères, J. (1998). "Special Issue: Contourites, turbidites and process interaction - Preface." *Sedimentary Geology*, 115(1-4), 1-1.

Stow, D., Faugères, J., Viana, A., and Gonthier, E. (1998). "Fossil contourites: a critical review." *Sedimentary Geology*, 115(1-4), 3-31.
Stow, D., Hernández-Molina, F., Alvarez Zarikian, C., and The Expedition 339 Scientists. (2013a). *Mediterranean Outflow: Environmental significance of the Mediterranean Outflow Water.*, Tokyo: Integrated Ocean Drilling Program Management International, Inc.
Stow, D., Hernández-Molina, F., E, L., Sayago-Gil, M., Díaz del Río, V., and Branson, A. (2009). "Bedform-velocity matrix: The estimation of bottom current velocity from bedform observations." *Geology*, 37, 327-330.
Stow, D., Hernández-Molina, F., Hodell, D., and Alvarez Zarikian, C. (2011b). "Mediterranean outflow:environmental significance of the Mediterranean Outflow Water and its global implications.", *Integrated Ocean Drilling Program Scientific Prospectus Addendum*.
Stow, D., Hernández-Molina, F., Llave, E., Bruno, M., García, M., Díaz del Rio, V., Somoza, L., and Brackenridge, R. (2013b). "The Cadiz Contourite Channel: Sandy contourites, bedforms and dynamic current interaction." *Marine Geology*, 343, 99-114.
Stow, D., and Holbrook, J. (1984). "North Atlantic contourites: an overview", in D. Stow and D. Piper, (eds.), *Fine-grained Sediments: Deep-water Processes and Facies*. London: Geological Society, pp. 245-256.
Stow, D., Hunter, S., Wilkinson, D., and Hernández-Molina, F. (2008). "The nature of contourite deposition", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites* Developments in Sedimentology, pp. 143-156.
Stow, D., Kahler, G., and Reeder, M. (2002d). "Fossil contourites: type example from an Oligocene palaeoslope system, Cyprus. ", in D. Stow, C. Pudsey, J. Howe, J. Faugères, and A. Viana, (eds.), *Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics.* . London: Geological Society, pp. 443-455.
Stow, D., and Mayall, M. (2000). "Deep-water sedimentary systems: New models for the 21st century." *Marine and Petroleum Geology*, 17(2), 125-135.
Stow, D., Pudsey, C., Howe, J., Faugères, J.-C., and Viana, A. (2002e). *Deep-Water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics*, London: Geological Society.
Stow, D., Reading, H., and Collinson, J. (1996). "Deep seas.", in H. Reading, (ed.), *Sedimentary Environments.* Oxford: Blackwell, pp. 395-454.
Stuiver, M., and Grootes, P. (2000). "GISP2 Oxygen Isotope Ratios." *Quaternary Research*, 53, 277-284.
SUERC, S. U. E. R. C. (n.d.). "AMS Programme". City: http://www.gla.ac.uk/centres/nercrcl/Analytical_new.htm.
Surlyk, F., Jensen, S., and Engkilde, M. (2008). "Deep channels in the Cenomanian-Danian Chalk Group of the German North Sea sector: Evidence of strong constructional and erosional bottom currents and effect on reservoir quality distribution." *Aapg Bulletin*, 92(11), 1565-1586.
Surlyk, F., and Lykke-Andersen, H. (2007). "Contourite drifts, moats and channels in the Upper Cretaceous chalk of the Danish Basin." *Sedimentology*, 54(2), 405-422.
SWIM Map Team. (2007). "Morphobathymetry of the Gulf of Cadiz, NE Atlantic. The SWIM Multibeam compilation Map 1:175 000", Euromargin, (ed.). City.
Talling, P., Masson, D., Sumner, E., and Malgesini, G. (2012). "Subaqueous sediment density flows: Depositional processes and deposit types." *Sedimentology*, 59, 1937–2003.
Tasianas, A. (2010). *Mud diapirism in the Gulf of Cadiz contourite depositional system: Study of the distribution, scale, size of these features and the effects on structural pattern and thickness of the contourite sediments around it.*, Heriot Watt Univeristy.
Taylor, R. (1987). *Radiocarbon Dating: An Archaeological Perspective*, Orlando: Academic Press.
Terrinha, P., Matias, L., Vicente, J., Duarte, J., Luis, J., Pinheiro, L., Lourenco, N., Diez, S., Rosas, F., Magalhaes, V., Valadares, V., Zitellini, N., Roque, C., Victor, L., and Team, M. (2009).

"Morphotectonics and strain partitioning at the Iberia-Africa plate boundary from multibeam and seismic reflection data." *Marine Geology*, 267(3-4), 156-174.

TGS. (2005). "PD00: Non-exclusive 2D survey". City: TGS Online Data Zone, pp. http://www.tgsnopec.com/specsheets/PD-00_Spec.pdf.

Thomdycraft, V., and Benito, G. (2006). "The Holocene fluvial chronology of Spain: evidence from a newly compiled radiocarbon database. ." *Quaternary Science Reviews*, 25(3-4), 223-234.

Torelli, L., Sartori, R., and Zitellini, N. (1997). "The giant chaotic body in the Atlantic Ocean off Gibraltar: New results from a deep seismic reflection survey." *Marine and Petroleum Geology*, 14(2), 125-138.

Toucanne, S., Mulder, T., Schonfeld, J., Hanquiez, V., Gonthier, E., Duprat, J., Cremer, M., and Zaragosi, S. (2007). "Contourites of the Gulf of Cadiz: A high-resolution record of the paleocirculation of the Mediterranean outflow water during the last 50,000 years." *Palaeogeography Palaeoclimatology Palaeoecology*, 246(2-4), 354-366.

Tucker, M. (1991). *Sedimentary petrology: an introduction to the origin of sedimentary rocks*, Oxford: Blackwell Science.

Vail, P., Audemard, F., Bowman, S., Eisner, P., and Perez-Cruz, C. (1991). "The stratigraphic signatures of tectonics, eustasy and sedimentology - an overview.", in G. Einsele, W. Ricken, and A. Seilacher, (eds.), *Cycles and Events in Stratigraphy.* Berlin: Springer, pp. 617-659.

Vail, P., Mitchum, R., and Thompson, S. (1977). "Seismic stratigraphy and global changes of sea-level. Part 3: Relative changes of sea level from coastal onlap.", in C. Payton, (ed.), *Seismic Stratigraphy - Applications to Hydrocarbon Exploration.*: AAPG, pp. 63-82.

Van Rooij, D., Iglesias, J., Hernández-Molina, F., Ercilla, G., Gomez-Ballesteros, M., Casas, D., Llave, E., De Hauwere, A., Garcia-Gil, S., Acosta, J., and Henriet, J.-P. (2010). "The Le Danois Contourite Depositional System: Interactions between the Mediterranean Outflow Water and the upper Cantabrian slope (North Iberian Margin)." *Marine Geology*, 274, 1-20.

Van Wagoner, J., Posamentier, H., Mitchum, R., Vail, P., Sarg, J., Loutit, T., and Hardenbol, J. (1988). "An overview of the fundamentals of sequence stratigraphy and key definitions.", in C. Wilgus, B. Hastings, C. Kendall, H. Posamentier, C. Ross, and J. Van Wagoner, (eds.), *Sea-level changes: an integrated approach.*: SEPM pp. 74-79.

Van Weering, T., Stoker, M., and Rebesco, M. (2008). "High-latitude contourites.", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites*. Developments in Sedimentology, pp. 457-489.

Vegas, R., Medialdea, T., Muñoz, M., Díaz del Río, V., and Somoza, L. (2004). "Nature and tectonic setting of the Guadalquivir Bank (Gulf of Cadiz, SW Iberian Peninsula)." *Revista de la Sociedad Geológica de España,*, 17, 49-60.

Viana, A. (2001). "Seismic expression of shallow- to deep-water contourites along the south-eastern Brazilian margin." *Marine Geophysical Researches*, 22(5-6), 509-521.

Viana, A. (2008). "Economic relevance of contourites.", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites*. Developments in Sedimentology, pp. 493-510.

Viana, A., Almeida Jr, W., and Almeida, C. (2001). "Upper slope sands: late Quaternary shallow-water sandy contourites of the Campos Basin, SW Atlantic Margin.", in D. Stow, C. Pudsey, J. Howe, J.-C. Faugères, and A. Viana, (eds.), *Deep-water Contourite Systems: Modern Drifts and Ancient Series, Seismic and Sedimentary Characteristics*. London: Geological Society, pp. 261-270.

Viana, A., and Almeida Jr., W. (2012). "Key factors controlling the application of the contourite concept for conventional and unconventional reservoirs."*VIII Congreso Geologico de Espana*. City: Geo-Temas: Oviedo, pp. 546.

Viana, A., Almeida Jr., W., Nunes, M., and Bulhões, E. (2007). "The economic importance of contourites", in A. Viana and M. Rebesco, (eds.), *Economic and Palaeoceanographic Significance of Contourite Deposits*. London: Geological Society, pp. 1-23.

Viana, A., Faugères, J., and Stow, D. (1998). "Bottom-current-controlled sand deposits - a review of modern shallow- to deep-water environments." *Sedimentary Geology*, 115(1-4), 53-80.
Viana, A., Hercos, C., WDJr, A., Magalhães, J., and Andrade, S. (2002). "Evidence of bottom current influence on the Neogene to Quaternary sedimentation along the northern Campos Slope, SW Atlantic Margin", in D. Stow, C. Pudsey, J. Howe, J.-C. Faugères, and A. Viana, (eds.), *Deep-water contourite systems: modern drifts and ancient series, seismic and sedimentary characteristics*. London: Geological Society, Memoirs, pp. 249-259.
Viana, A., and Rebesco, M. (2007). *Economic and Palaeoceanographic Significance of Contourite Deposits*, London: Geological Society.
Violante, R., Paterlini, C., Costa, I., Hernández-Molina, F., Segovia, L., Cavallotto, J., Marcolini, S., Bozzano, G., Laprida, C., Chapori, N., Bickert, T., and Spieß, V. (2010). "Sismoestratigrafia y evolución geomorfológica del talud continental adyacente al litoral del este bonaerense, Argentina." *Latin American Journal of Sedimentology and Basin Analysis.*, 17, 33.
Visher, G. (1969). "Grain size distributions and depositional processes." *Journal of Sedimentary Petrology*, 39, 1074-1106.
Voelker, A., Lebreiro, S., Schönfeld, J., Cacho, I., Erlenkeuser, H., and Abrabtes, F. (2006). "Mediterranean outflow strengthening during northern hemisphere coolings: A salt source for the glacial Atlantic?" *Earth and Planetary Science Letters*, 245, 39-55.
Walker, M. (2005). *Quaternary Dating Methods*, Chichester: John Wiley and Sons Ltd.
Walker, R., and James, N. (1992). "Facies, models: response to sea-level change.", in R. Walker and N. James, (eds.), *Facies Models: Response to Sea-Level Change.* Calgary: Geological Society of Canada, pp. 1-14.
Weaver, P., Wynn, R., Kenyon, N., and Evans, J. (2000). "Continental margin sedimentation, with special reference to the north-east Atlantic margin." *Sedimentology*, 47, 239-256.
Wehausen, R., and Brumsack, H.-J. (1999). "Cyclic variations in the chemical composition of eastern Mediterranean Pliocene sediments: a key for understanding sapropel formation." *Marine Geology*, 153, 161-176.
Weimer, P., and Slatt, R. (2004). *Petroleum Systems of Deepwater Settings*: Society of Exploration Geophysicists and European Association of Geoscientists and Engineers.
Weltje, G., and Tjallingii, R. (2008). "Calibration of XRF core scanners for quantitative geochemical logging of sediment cores: Theory and application." *Earth and Planetary Science Letters*, 274, 423-438.
Wentworth, C. (1922). "A scale of grade and class terms for clastic sediments." *Journal of Geology*, 30, 377-392.
Wetzel, A. (1991). "Ecological interpretation of deep-sea trace fossil communities." *Palaeogeography, Palaeoclimatology, Palaeoecology*, 85, 47-69.
Wetzel, A., Werner, F., and DAV, S. (2008). "Bioturbation and biogenic sedimentary structures in contourites.", in M. Rebesco and A. Camerlenghi, (eds.), *Contourites.*: Developments in Sedimentology, pp. 183-202.
Wheeler, A., Kozachenko, M., Beyer, A., Foubert, A., Huvenne, V., Klages, M., Masson, D., Olu-Le Roy, K., and Thiede, J. (2005). "Sedimentary processes and carbonate mounds in the Belgica mound province, Porcupine Seabight, NE Atlantic.", in A. Freiwald and J. Roberts, (eds.), *Cold-water corals and ecosystems.* Heidelberg: Springer-Varlag, pp. 571-603.
Yarincik, K., Murray, R., Lyons, T., Peterson, L., and Haug, G. (2000). "Oxygenation history of bottom waters in the Cariaco Basin, Venezuela, over the past 578,000 years: Results from redox-sensitive metals (Mo, V, Mn, and Fe)." *Paleoceanography*, 15, 593-604.
Youbin, H., Jinxiong, L., Xiangdong, L., Zhenzhong, G., and Zhan, W. (2011). "Evidence of internal wave and internal-tide deposits in the Middle Ordovician Xujiajuan Formation of the Xiangshan Group, Ningxia, China." *Geo-Marine Letters*, 31, 509-523.

Youbin, H., Zhengzhong, G., Jinxiong, L., Shunshe, L., and Xuefeng, L. (2008). "Characteristics of internal-wave and internal-tide deposits and their hydrocarbon potential." *Petroleum Science*, 2008, 37-44.

Zenk, W. (1970). "On the temperature and salinity structure of Mediterranean-Water in northeast-Atlantic." *Deep-Sea Research*, 17(3), 627–630.

Zenk, W. (1975). "On the Mediterranean outflow west of Gibraltar." *Meteor Forschungsergeb*, 16, 23-34.

Zhengzhong, G., and Eriksson, K. (1998). *Deep-water Traction Current Deposits - A Study of Internal Tides, Internal Waves, Contour Currents and Their Deposits,.* Bejing: Science Press.

Zhenzhong, G., and Eriksson, K. (1998). "Internal tides, internal waves and their deposits in modern oceans", in G. Zhenzhong, K. Eriksson, H. Youbin, L. Shunshe, and G. Jianhua, (eds.), *Deep-water Traction Current Deposits – A study of internal tides, internal waves, contour currents and their deposits.* . Beijing: Science Press, pp. 1-24.

Zitellini, N., Gracia, E., Matias, L., Terrinha, P., Abreu, M., DeAlteriis, G., Henriet, J., Danobeitia, J., Masson, D., Mulder, T., Ramella, R., Somoza, L., and Diez, S. (2009). "The quest for the Africa-Eurasia plate boundary west of the Strait of Gibraltar." *Earth and Planetary Science Letters*, 280(1-4), 13-50.