

# A Pliocene mixed contourite–turbidite system offshore the Algarve Margin, Gulf of Cadiz: Seismic response, margin evolution and reservoir implications



Rachel E. Brackenridge<sup>a,\*</sup>, F.J. Hernández-Molina<sup>b,d</sup>, D.A.V. Stow<sup>a</sup>, E. Llave<sup>c</sup>

<sup>a</sup> IPE-ECOSSE, Heriot Watt University, Edinburgh EH14 4AS, UK

<sup>b</sup> Facultad de Ciencias del Mar, Universidad de Vigo, 36200 Vigo, Spain

<sup>c</sup> Instituto Geológico y Minero de España (IGME), c/Ríos Rosas 23, 28003 Madrid, Spain

<sup>d</sup> Department of Earth Sciences, Royal Holloway University of London, Egham, Surrey TW20 0EX, UK

## ARTICLE INFO

### Article history:

Received 7 January 2013

Received in revised form

20 May 2013

Accepted 21 May 2013

Available online 11 June 2013

### Keywords:

Contourite drift

Mixed system

Algarve Margin

Mediterranean Outflow Water

Gulf of Cadiz

Contourite hydrocarbon reservoir potential

## ABSTRACT

A buried mixed contourite–turbidite system has been identified in the Pliocene succession of the Algarve basin in the northern Gulf of Cadiz. This margin is currently dominated by the Mediterranean Outflow Water and associated contourite deposition. Analysis of seismic data along with careful geographical and oceanographic reconstructions of the margin show 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. The contourite drift can be distinguished from down-slope (turbiditic and mass transport 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 dominant down-slope (most likely turbidite) system sourced mainly from the northeast. There is clear evidence of contourite reworking at Seismic Unit P2, where upslope progradation and a sheeted morphology are observed. High amplitude reflections are thought to be a result of more vigorous bottom currents in the early Upper Pliocene that were capable of redistributing coarser sediments. However, in the northeast of the study area a thick sequence of chaotic seismic facies has been interpreted as mass transport deposits sourced from the north indicate that 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 (*ca.* 2.6 Ma), highly erosive discontinuities and high amplitude seismic reflections are evidence of pronounced intensification of the Mediterranean Outflow Water and a move to a fully contourite-dominated slope. Mixed turbidite–contourite systems such as the one identified in the Algarve Basin could provide impressive petroleum potential where downslope clastics are winnowed and reworked by bottom water currents to leave good reservoir properties. Here, we present a conceptual model for sheeted drifts as hydrocarbon reservoirs in the subsurface.

© 2013 Published by Elsevier Ltd.

## 1. Introduction

The term ‘contourite’ is accepted for those sediments deposited or substantially reworked by bottom currents (Heezen et al., 1966; Rebesco and Camerlenghi, 2008). Major accumulations of

\* Corresponding author. Tel.: +44 (0)131 451 3699.

E-mail addresses: [rachel.brackenridge@pet.hw.ac.uk](mailto:rachel.brackenridge@pet.hw.ac.uk) (R.E. Brackenridge), [fjhernan@uvigo.es](mailto:fjhernan@uvigo.es) (F.J. Hernández-Molina), [dorrik.Stow@pet.hw.ac.uk](mailto:dorrik.Stow@pet.hw.ac.uk) (D.A.V. Stow), [e.llave@igme.es](mailto:e.llave@igme.es) (E. Llave).

contourite deposits are referred to as “drifts”. Where currents are strong enough, a variety of erosional and depositional features are developed (Evans et al., 1998; García et al., 2009; Hernández-Molina et al., 2008; Masson, 2001; Nelson et al., 1993; Preu et al., 2013; Stow et al., 2009; Stow and Mayall, 2000). An association of various drifts and related erosional features is commonly termed a contourite depositional system (CDS) (Hernández-Molina et al., 2003, 2008). Mixed contourite–turbidite systems are developed where bottom currents have interacted with down-slope processes (Faugères et al., 1999; Rebesco and Camerlenghi, 2008).

The use of seismic data is vital to contourite drift identification and interpretation. Drifts are primarily identified by external geometry and internal architecture. This is useful for drifts of mounded morphology, but much more challenging with aggradational sheeted drifts. For these, the seismic facies could be an additional important diagnostic tool. It is, therefore, of great importance to fully understand the acoustic response of sedimentary drifts. Work by Faugères et al. (1999), Howe (2008), Nielsen et al. (2008) and Shanmugam (2006) have provided an initial overview to the seismic response of contourites and outline the processes by which to analyse and describe drifts using geophysical data. There are several types of contourite drifts, defined mainly on their morphological, sedimentological and seismic characteristics (Faugères and Mulder, 2011; Faugères et al., 1999; McCave and Tucholke, 1986; Rebesco, 2005; Rebesco and Camerlenghi, 2008; Rebesco and Stow, 2001; Stow et al., 2002b). The generation of each drift type is controlled by a complex set of factors, most importantly the local morphology of the seabed, the bottom water current conditions and the sediment supply (Faugères and Stow, 1993; Faugères et al., 1999; Shannon et al., 2005; Viana et al., 1998). Often, a complex CDS is formed, consisting of many different drift types and erosional elements. A given contourite accumulation may also evolve over time between drift types. Since the primary identification of contourites is usually by overall drift geometry (Nielsen et al., 2008), many known drifts are those with some topographic relief from the seabed, i.e. those of mounded

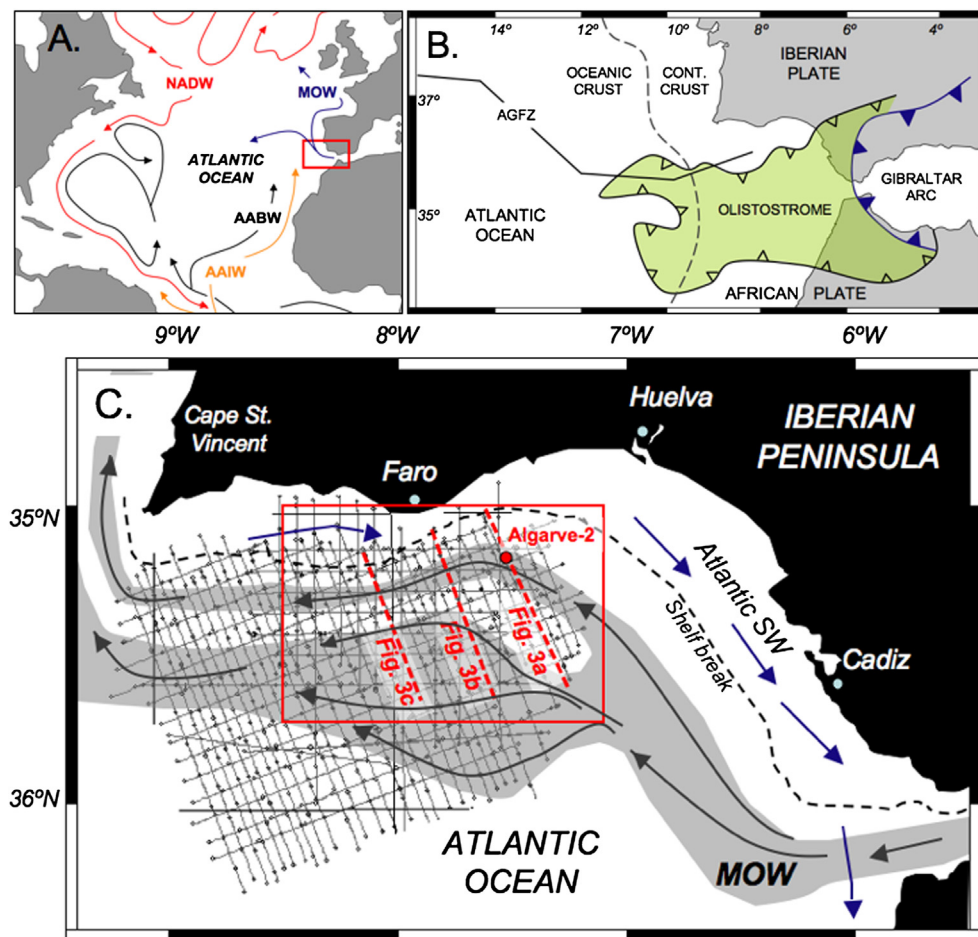
external morphology. Much less is known about the identification of sheeted drifts both on the seabed and in the subsurface. In recent years, the hydrocarbon potential of contourite deposits has been explored (Viana et al., 2007), and it is seen that clastic reservoir (sand-rich) facies are most commonly found as sheeted drifts, or as localized channel accumulations. It is therefore of great importance that these drifts are characterized and made identifiable in the subsurface and distinguishable from down-slope deposits.

This work examines a buried contourite sheeted drift within a mixed system in the Gulf of Cadiz using seismic data. The key aims are therefore; 1) Characterize the along- and down-slope components of the system on all scales (drift-, depositional unit- and seismofacies-scale); 2) Assess the interaction between along- and down-slope processes; 3) Propose a depositional model for the Algarve Margin Pliocene section; 4) Identify any key criteria to aid the identification of sheeted contourite drift systems elsewhere; and 5) Use the above information to make conclusions on the identification of contourites in the subsurface for hydrocarbon exploration.

## 2. Geological and oceanographic setting

### 2.1. Geological setting and margin evolution

The study area is located along the Algarve Margin in the western Gulf of Cadiz (Fig. 1A). This region has had a complex geodynamic



**Figure 1.** A) Location map for the study area (boxed). AABW = Atlantic Bottom Water; AAIW = Atlantic Intermediate Water; MOW = Mediterranean Outflow Water; NADW = North Atlantic deep Water. B) Tectonic and Location Map for the study Area. Modified from Maldonado and Nelson (1999). C) 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 line indicated position of the seismic lines on Fig. 3. MOW = Mediterranean Outflow Water. Atlantic SW = Atlantic Surface Water. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

history as a result of its situation between the African and Eurasian continental plates (Flinch et al., 1996; Medialdea et al., 2009; Zitellini et al., 2009). Geophysical studies have aided the interpretation of the margin evolution, which has been varied and complex (Gutscher et al., 2002; Maldonado et al., 1999; Medialdea et al., 2004; Nelson and Maldonado, 1999). The plate boundary between the African and Eurasian plates has 'jumped' (Srivastava et al., 1990) and at times the Iberian plate acted independently (Roest and Srivastava, 1991). Three key events have been identified as crucial for the modern set-up of the margin (Maldonado et al., 1999): 1) Late Mesozoic passive margin development that occurred post-rift and sea-floor spreading as the Tethys and Atlantic Oceans opened; 2) the Cenozoic convergence of the African and Eurasian plates in an N–S direction; and 3) the extensional collapse of mountains to the east and resulting olistostrome emplacement, named the Cadiz Allochthonous Unit (Medialdea et al., 2004) over the Gulf of Cadiz. A change in compression orientation in the Late Miocene–Pliocene may also have played an important part in affecting the sedimentation pattern of the margin (Zitellini et al., 2009).

Today, a compressional tectonic regime is ongoing in the Gulf of Cadiz, although it is slowing and the margin is moving towards more stable conditions (Rosenbaum et al., 2002). The Eurasian and African plates are currently converging at a rate of approximately 4 mm/yr in an NE–SW orientation (Maldonado et al., 1999). To the west, the Azores–Gibraltar Fracture Zone (AGFZ) results in strike-slip tectonics in the west of the Gulf (Fig. 1B). To the East, mounting evidence points towards a region of forced lithospheric subduction of oceanic crust eastwards under the Alboran and Mediterranean Seas (Gutscher et al., 2002; Royden, 1993). This results in slab rollback and subsequent uplift and extensional tectonics in the eastern Gulf of Cadiz and Gibraltar regions. Elsewhere neotectonics play an important role along the margin. The deposition of an unstable allochthonous unit in the middle to late Miocene has led to intense halokinesis along the margin, which affects the modern day sea floor. Triassic and Mid-Miocene marls and salts have pierced overlying sediments forming diapiric ridges and adjacent depocentres (Hernández-Molina et al., 2006; Llave et al., 2007; Somoza et al., 2003). In all, the margin is a tectonically complex and active one. This has important implications for both modern and past sedimentation trends.

## 2.2. Oceanographic setting

The hydrodynamic framework of the Gulf of Cadiz is dominated by the water exchange between the Atlantic Ocean and the Mediterranean Sea. The Strait of Gibraltar acts as the gateway for exchange between the warm saline Mediterranean Outflow Water (MOW) and the overlying Atlantic Inflow Water (Baringer and Price, 1999; Llave et al., 2007). Much physical oceanographic research has been carried out on the MOW in recent decades and its current properties and route are now well constrained (Baringer and Price, 1999; García Lafuente and Ruiz, 2007; Serra et al., 2010).

The MOW is composed of a mixture of water masses sourced from the Mediterranean Basin; the Levantine Intermediate Water forming approximately two thirds, and the remainder sourced from the Western Mediterranean Deep Water. The constricted basin of the Mediterranean with its arid climate provides favourable conditions for the formation of warm, highly saline, dense water of 13 °C, 36.5‰ (Ambar and Howe, 1979). The water mass accelerates through the narrow gateway of the Strait of Gibraltar, where they are thought to locally reaching velocities in excess of 2.5 m s<sup>-1</sup> (Ambar and Howe, 1979; Mulder et al., 2003) and moves north-westwards along the mid-slope of the Gulf of Cadiz (Fig. 1C). Density-driven descent and mixing with overlying Atlantic Waters results in decreasing salinity along the margin from SE to NW

(Baringer and Price, 1997) and eventually the MOW leaves the seabed and reaches a neutral buoyancy at a depth of 1400 m offshore the Cape of St Vincent, where it begins to raft above the North Atlantic Deep Water.

The MOW is restricted to a core approximately 10 km wide as it accelerates through the Strait of Gibraltar. Along the mid-slope of the Gulf of Cadiz however, the core can exceed 80 km in width (Baringer and Price, 1997) and forms a broad, sluggish flow. The velocity is locally enhanced where late Cenozoic neotectonics have created diapiric ridges oblique to the MOW flow direction (García et al., 2009). These ridges, predominantly marly in composition (Maldonado et al., 1999), have undoubtedly been responsible for the splitting of the water mass into numerous distinctive cores (Fig. 1C), although vertical layering within the water core has also been proposed as an additional control. There are two principal water cores- one main upper water core and a lower core that further divides to form the Intermediate Branch, the Principal Branch and the Southern Branch (Llave et al., 2007). Each branch demonstrates unique physical oceanographic properties, such as salinity, temperature and average velocity (Ambar and Howe, 1979; Borenas et al., 2002; Zenk, 1970). Overall, the Upper Core (which influences the study area) is a smaller, warm, less saline water mass when compared to the lower core (Llave et al., 2007).

The movement of water masses through the Strait of Gibraltar was first recorded in salinity data acquired in the early 1900s (Nielsen, 1912) and since then, numerous studies on the water shows 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 (Hsü et al., 1973). This signifies that the Strait of Gibraltar opened at this time so that the exchange of water was possible between the Atlantic Ocean and the Mediterranean Sea. The precise 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 beginning of the Early Pliocene (Hernández-Molina et al., 2009b; Llave et al., 2010; Raddatz et al., 2011; Rogerson et al., 2012). Since that time, variations in the MOW are clear from proxy data and the high cyclicity observed in acoustic data. These variations point towards a more vigorous and denser 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; Voelker et al., 2006) and a more vigorous less denser upper branch of the MOW during the recent highstand period (Rogerson et al., 2005; Stow et al., 2002a). A clear separation between responses to climatic/eustatic-induced changes and tectonic movements remains challenging, and will be explored further in this study.

## 2.3. Contourite depositional system (CDS)

The MOW directly affects the sediments deposited in the study area, and the rest of the Gulf of Cadiz. Sufficient velocities have been maintained to form large contourite drifts along the entire length of the margin from the Strait of Gibraltar to the Cape of St Vincent and beyond along the western and northern Iberian continental margins (Hernández-Molina et al., 2011; Van Rooij et al., 2010). As both depositional and erosional products can be present along a margin influenced by bottom currents, it is practical to refer to contourites as depositional systems. A contourite depositional system (CDS) will form along any continental margin where along-slope processes dominate over mass wasting, turbidity currents and pelagic/hemipelagic settling processes (Hernández-Molina et al., 2008). Each depositional system will begin in some region that can provide a mechanism for enhanced bottom water velocity. It will

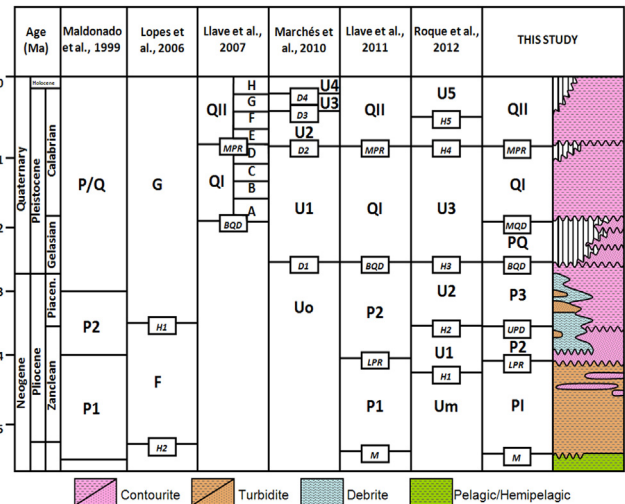
terminate where the transport capacity of the contour current is diminished so that it is no longer capable of dominating over other depositional processes. A CDS will evolve over time and space, controlled by climatic and oceanographic changes in addition to local tectonic activity that can affect the margin and water masses such as oceanic gateways and halokinesis.

The Gulf of Cadiz CDS initiates where the MOW overflows into the Atlantic Ocean as a highly saline dense water mass and is accelerated through the narrow conduit which connects the two oceans: the Strait of Gibraltar (Howe, 1982). Coriolis Forces push the water mass northwards, moving it around the mid-slope in the Gulf of Cadiz and extending round the west Iberian Margin. Close to the Strait of Gibraltar, current-meter moorings have recorded bottom water velocities in excess of  $1 \text{ m s}^{-1}$  (Baringer and Price, 1999; García et al., 2009; Hernández-Molina et al., 2011) and as a result, erosion and sand-deposition are the dominant ongoing processes. Features 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., 2008) with laterally extensive erosional surfaces in the east moving to discrete contourrite channels in the west where outcropping diapiric structures manipulate the bottom water core. Contourrite moats occur more distal still (from the Strait of Gibraltar) and are associated with depositional features. Many contourrite drifts are observed along the margin, evolving between drift types over space and time. 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 Strait of Gibraltar (Nelson et al., 1999). Detailed investigations of the systems has exposed five distinct 'morphosedimentary sectors' (Hernández-Molina et al., 2003, 2006; Llave et al., 2007) each showing different characteristics and depositional/erosional features. (1) Proximal scour and sand ribbons sector; (2) Outflow-sedimentary lobe sector; (3) Channels and ridges sector; (4) Active contourrite drift sector; (5) Submarine canyons sector. The study area under investigation here is located mainly in the active contourrite drift sector (sector 4) and extends some way into the submarine canyons sector (see Fig. 5 in Hernández-Molina et al., 2006).

On a larger scale, this CDS can be compared and contrasted to others found on continental margins around the oceans. This system is classed as a mixed contourrite–turbidite system, but unlike many other margins (Locker and Laine, 1992; Rebesco et al., 2002; Viana, 2001; Viana et al., 2002) along-slope processes now dominate along the mid-continental slope and down-slope processes dominate at greater depths on the lower continental slope and abyssal plain (Hernández-Molina et al., 2011). Other features of this margin that makes it markedly different from others, is the lack of a continental rise and relatively fewer down-slope submarine canyons than would be expected (attributed to the large nature of the margin fluvial system). The first feature could be accounted for by the unstable substratum in the Gulf of Cadiz: the 'Cadiz Allocthonous Unit', and the second has been linked to the vigorous water masses circulation, which inhibit the down-slope processes on the upper and middle slope (Hernández-Molina et al., 2006).

### 3. Past work in the region

Early studies on the regional tectonostratigraphic evolution of the Gulf of Cadiz identified major discontinuities bounding at least two seismic units within the Pliocene (Maldonado et al., 1999). More localized studies on the Algarve Margin have resulted in dispute over 1) the names, 2) the age and 3) the number of major discontinuities in the study area (Llave et al., 2011; Lopes et al., 2006; Marches et al., 2010; Roque et al., 2012) (Fig. 2) Much of this confusion and conflict derives from interpretations based on the analysis of very old seismic data from the 1970s, or low



**Figure 2.** A number of past studies have been carried out. General consensus is nearing in the Quaternary section; however the Pliocene is refusing to yield a robust stratigraphy to date. This study identifies three units in the Pliocene and a highly eroded section in the Lowermost Quaternary. From Llave et al. (2007, 2011), Lopes et al. (2006), Maldonado and Nelson (1999), Marches et al. (2010) and Roque et al. (2012).

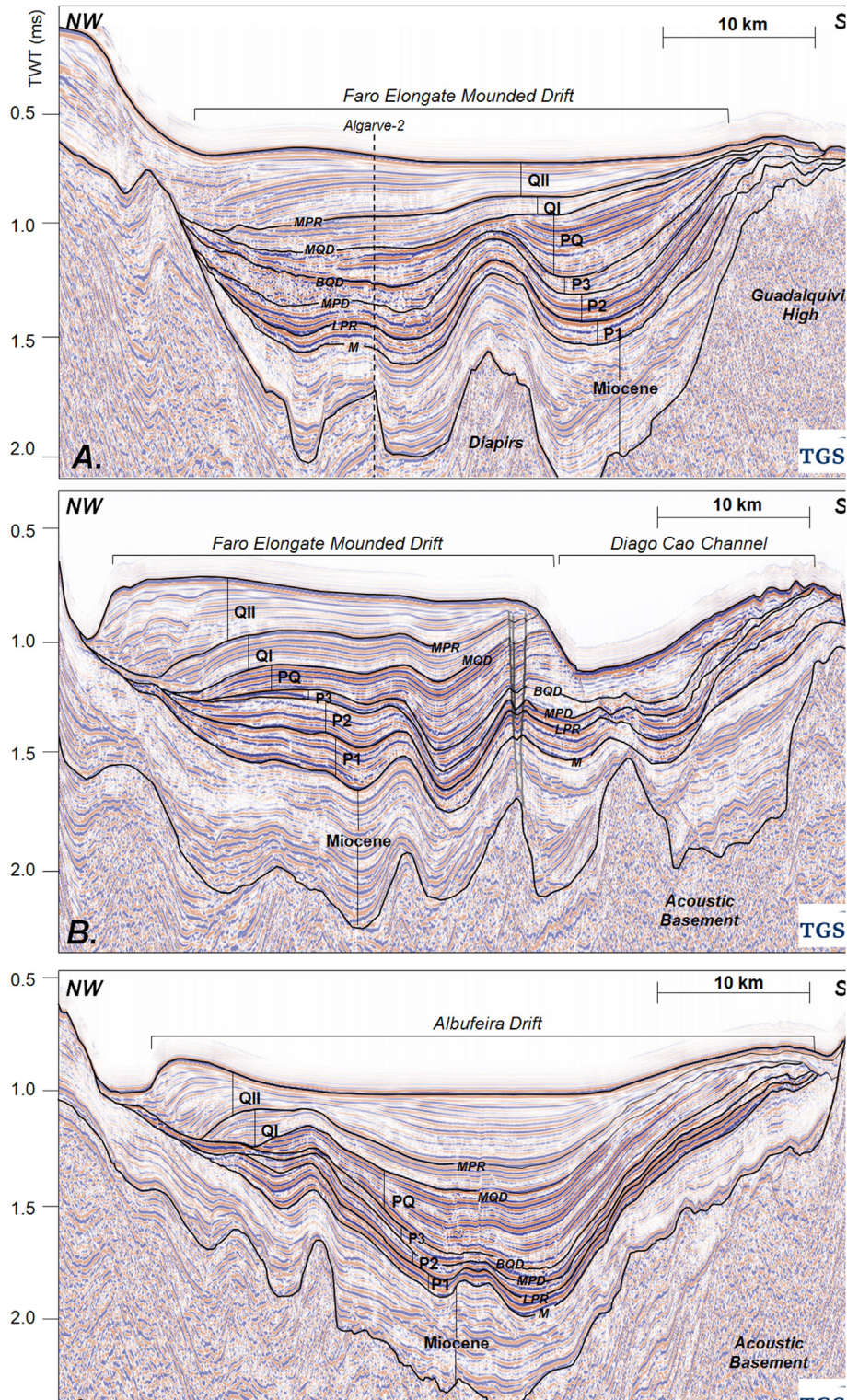
frequency, deep-penetrating data that gives much lower resolution. Most recent work points towards agreement on Quaternary discontinuities, however the Pliocene section has remained poorly studied and unwilling to provide a robust stratigraphy.

### 4. Data and methods

An extensive 2D seismic survey database was used (Fig. 1C), comprising two surveys. Survey PD00 was acquired by TGS-NOPEC in 2000 using a tuned bolt array with a shot point interval of 12.5 m (TGS, 2005). Survey PR00 was acquired at an unknown earlier date, but reprocessed in 2000 with survey PD00 (George, 2011). A total of 95 lines along the Portuguese margin of the Gulf of Cadiz make up the data set, between 160 and 320 km WNW of the Gibraltar Gateway. These seismic lines cover the outer shelf and extend down-slope 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 includes a detailed bathymetric map and marine gravity (TGS, 2005; Zitellini et al., 2009). All available data was compiled and uploaded to the interpretation software, in this case IHS Kingdom 8.5.

In general, the survey shows moderate to high quality, decreasing with depth. Poor resolution is observed at depths greater than 2.5–3 s 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 (Loseth et al., 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.

Work in the region has been carried out to identify key discontinuities in the subsurface, which relate to changes in the depositional style associate with oceanographic events along the slope. The data has been tied to industry borehole Algarve-2 (Fig. 1C), which was drilled by Esso in 1982 (Algarve-2, 1982). This has been used to confirm the depths and ages of the major Late Miocene and Pliocene discontinuities with some confidence at a regional scale. Although there will be increased risk in reflection mapping away from the boreholes, care was taken to map discontinuities by observing strong reflections in seismic (Sheriff and



**Figure 3.** Location of seismic lines indicated on Fig. 1C. Seismic sequences are labelled and the key discontinuities named. MPR = Mid Pleistocene Reflection; MQD = Mid Quaternary Reflection; BQD = Base Quaternary Discontinuity; UPD = Upper Pliocene Discontinuity; LPR = Lower Pliocene Revolution; M = Top Miocene Discontinuity. Depositional sequences P1-QII refer to those outlined in Fig. 2.

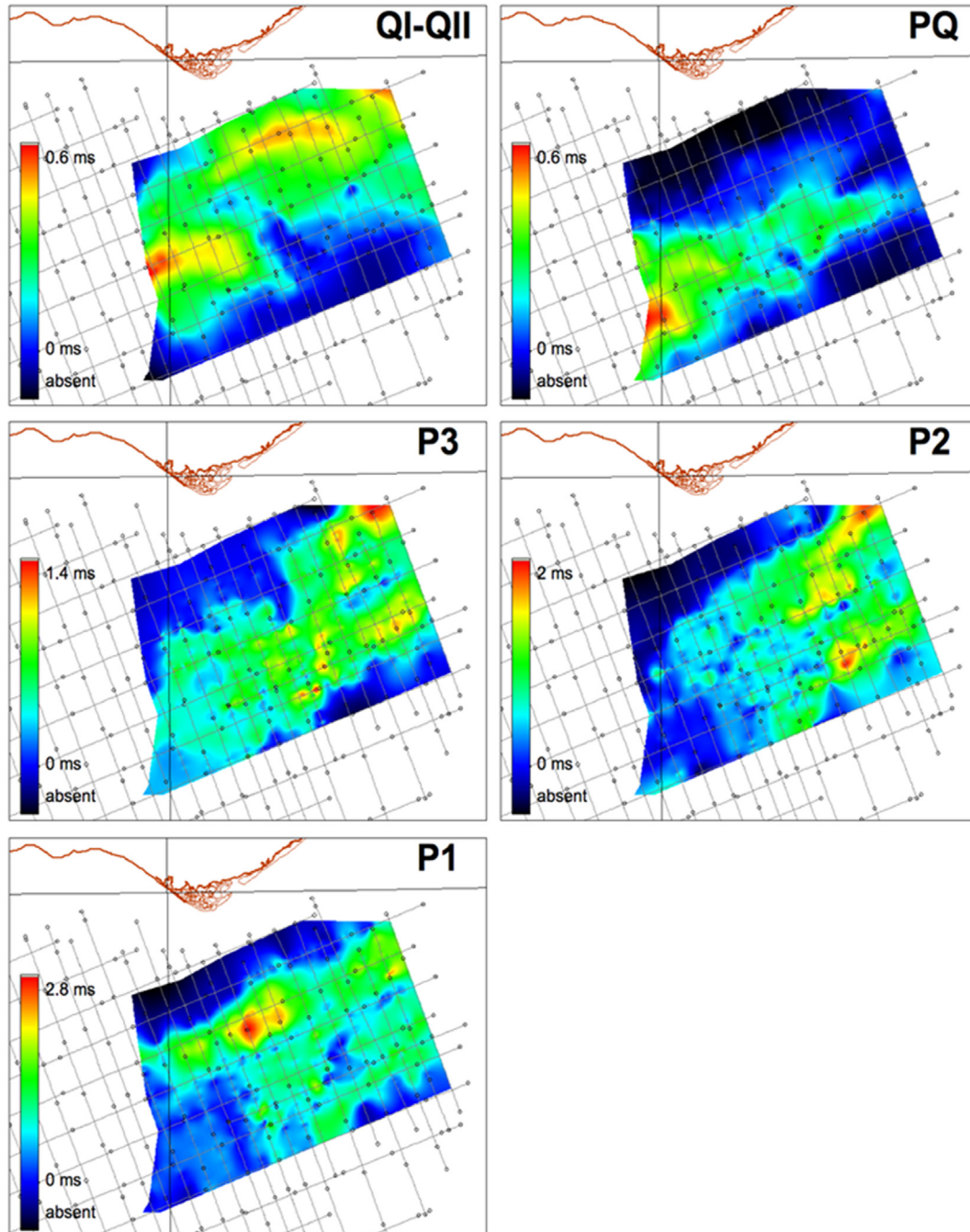
Geldart, 1995) and, more importantly, observing reflection terminations (onlapping and downlapping as well as erosional truncations of reflections). In addition, the regional Quaternary ages given by Llave et al. (2001, 2007, 2011); Lopes et al. (2006); Hernández-Molina et al. (2002, 2006); Marches et al. (2010) and Roque et al. (2012) have been considered for the final chronostratigraphic framework.

Once picked, discontinuities were mapped. Key horizons are: the seabed, six discontinuities within the Pliocene and lowermost Quaternary section, and the acoustic basement (Fig. 3). Contour maps for these horizons were produced using standard methods,

along with isochron maps for different sections in the Pliocene succession (Fig. 4). This work builds on that carried out by Hernández-Molina et al. (2006), Llave et al. (2001), (2007) and Stow et al. (2002a).

### 5. Results: the seismic response of the Pliocene section

The Late Miocene to Quaternary sediment cover along the Gulf of Cadiz margin is characterized by major discontinuities which have been used to aid interpretation (Fig. 3). Each seismic sequence has different acoustic characteristics, and here they will be



**Figure 4.** Isochron (time) maps for depositional sequences P1-QII. Reds are depocentres. A clear contrast in the focus of deposition between the Quaternary and the Pliocene sections. A major region of absent sedimentation (erosion) is seen in PQ.

outlined, including the first detailed description of the features of a contourite sheeted drift in the Lower Pliocene (Unit P2 in Fig. 3). 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.

### 5.1. Upper Miocene

Although outside the scope of this paper, it should be noted that 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. Maximum sediment thickness between the base Pliocene and top acoustic basement is up to 0.75 ms TWT, although the formation pinches out along many of the structural highs. The Miocene succession is heavily deformed, now observed as palaeorelief in the seismic data. Deposition of the olistostrome mass: the Cadiz Allochthonous Unit (Maldonado et al., 1999; 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.

### 5.2. Seismic Unit P1

#### 5.2.1. Bounding discontinuities

The basal discontinuity of Seismic Unit P1 is defined by a marked change in seismofacies and forms a major onlap surface (Fig. 5). It has been dated as the latest Miocene at ~5.3 Ma (Llave et al., 2011) and approximately marks the Miocene–Pliocene boundary. It has been previously named Discontinuity M (Llave et al., 2010, 2011)

and it should be noted that this differs in age from the Roque et al. (2012) Discontinuity M, which instead marks the base of the Miocene. There are some local evidences across the study area that this discontinuity represents a smooth erosional surface. The overlying seismic unit is here named P1 to correlate to the (Llave et al., 2010, 2011) classification scheme and associates, in part, to the base of U1 in the Roque et al. (2012) sequence classification (Fig. 2). The unit is dated as the Early Zanclean.

#### 5.2.2. Distribution

Figure 4 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. To the north, it is onlapping onto the palaeoslope relief and in places onto tectonic highs.

#### 5.2.3. Seismic character and evolution across the study area

The 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 up the sequence, evolving towards high amplitude, laterally extensive reflections that top the sequence. This is in stark contrast to the underlying weak to semi-transparent and more chaotic seismofacies of the Late Miocene. The package has been deformed by late Tertiary tectonics. Deformation includes faulting, displacement due to the uplift of the Guadalquivir High (Fig. 3) and localized deformation by halokinesis.

### 5.3. Seismic Unit P2

#### 5.3.1. Bounding discontinuities

The discontinuity separating Seismic Units P1 and P2 is the most subtle of the discontinuities in studied sedimentary record across the study area. Although largely conformable with the underlying P1 seismic package, it locally marked as an onlap surface (Fig. 5). In compliance with Llave et al. (2011), this discontinuity 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 localized upslope progradation along the continental slope in contrast to the onlap observed in the underlying P1 sequence.

#### 5.3.2. Distribution

P2 reaches its maximum thickness in the northeast of the study area, where it is 0.15 ms (Fig. 4). Maximum thicknesses coincide with an area of chaotic seismofacies (Fig. 3A). There is also a depocentre in the southeast (Fig. 4). Towards the west, the package thins considerably and in places it is completely absent where it has been cut by later erosional surfaces.

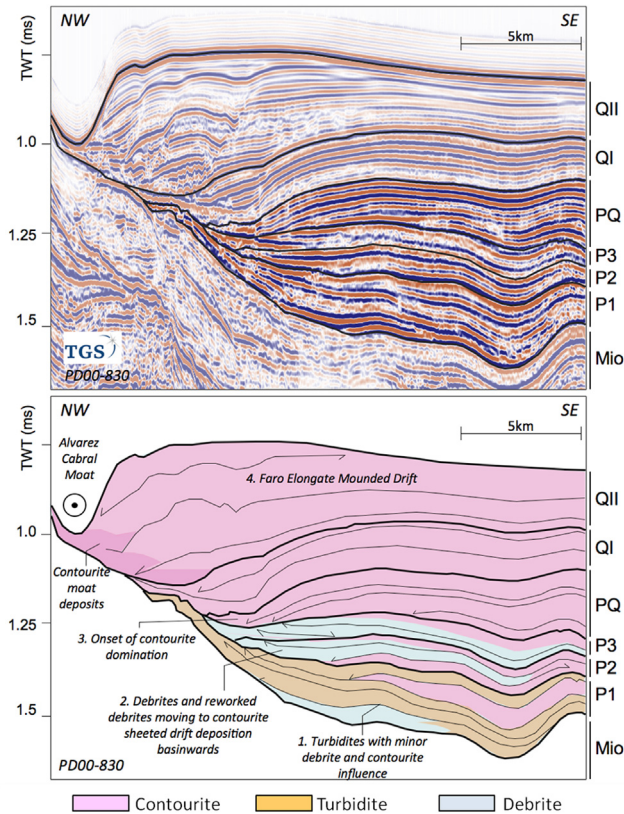
#### 5.3.3. Seismic character and evolution across the study area

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 seismofacies in P2. The package itself shows varied character across the region. To the northeast, a thick succession of chaotic seismofacies dominates. However, basinwards and westwards along-slope, this evolves towards high amplitude, parallel reflections.

### 5.4. Seismic Unit P3

#### 5.4.1. Bounding discontinuities

The high amplitude reflections of Seismic Unit P2 make way for more transparent facies over large swaths of the study area (Fig. 3A).



**Figure 5.** Detailed seismic section from line PD00-830 (Fig. 3B.) 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 thin Upper Pliocene P3 unit is bounded by the Upper Pliocene Discontinuity (UPD) at its base and the Base Quaternary Discontinuity (BQD) on top. This unit is previously identified by Roque et al. (2012). The basal discontinuity is marked by a change in seismofacies in the south east of the study area and localized onlap and downlap. There is some localized evidence that this is an erosional discontinuity (Fig. 5), and (Llave et al., 2001) have noted its erosive character. Data from industry borehole Algarve-2 indicate the overlying sequence P3 is Late Pliocene (Early Piacenzian) in age.

#### 5.4.2. Distribution

Seismic Unit P3 has been heavily eroded by later events along the continental margin and is completely absent across much of the north 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 is maintained with some thinning to the west (Fig. 4).

#### 5.4.3. 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 characterize the northeast of the study area whereas semi-continuous, parallel reflections are seen in the remaining region.

### 5.5. Seismic Unit PQ

#### 5.5.1. Bounding discontinuities

The BQD, which is easily distinguished by its high amplitude, marks the base of Seismic Unit PQ and the onset of contourite-dominated deposition along the margin (Fig. 3). Previous studies have dated this discontinuity 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 locally highly erosive nature in the northeast of the study area where erosional truncations are seen (Fig. 3A). In this study, the erosional discontinuity has been named the Lower-Quaternary Discontinuity (LQD).

#### 5.5.2. Distribution

The seismic unit has been heavily eroded in the northeast 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), 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 (e.g. Fig. 3A).

#### 5.5.3. Seismic character and evolution across the study area

The intense erosion along the slope has left a partially 'missing sequence' that 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, highly erosional discontinuities have been identified within the section. High amplitude, laterally extensive aggradational seismic reflections with many erosional truncations are seen within the sequence.

### 5.6. Mid-upper Quaternary

The Quaternary to recent section is marked by numerous discontinuities, many highly erosional in nature. Seismic sequences are highly progradational and aggradational in nature 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). 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 paper. They have been examined in detail in Llave et al. (2001, 2007).

## 6. Discussion

### 6.1. Pliocene depositional model for the Algarve Margin

Using seismic stratigraphic analysis, this study identifies four key successions within the Pliocene to Lowermost Quaternary section along the Algarve Margin. These have been attributed to the changing dominance of along- and down-slope processes leading to the eventual evolution of a contourite depositional system (CDS). 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 Pliocene mixed system has been described in detail for first time with interacting down-slope and along-slope processes, confirming some of the findings by Roque et al. (2012). The region therefore provides a good opportunity to analyse the differing acoustic responses of the sediments deposited by these processes and uses the conclusions to better identify sheeted contourite drifts elsewhere in the subsurface.

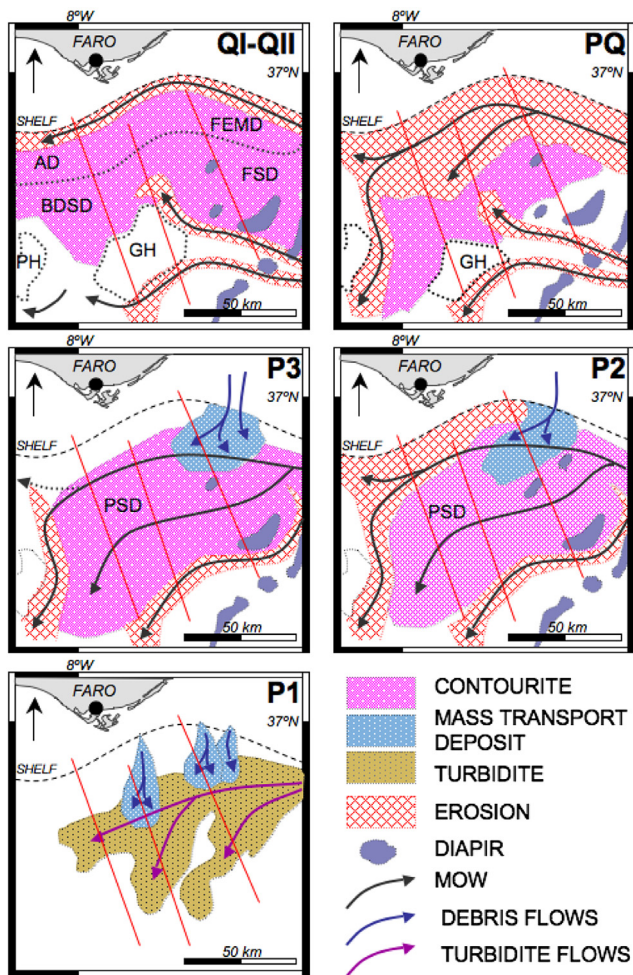
#### 6.1.1. Seismic Unit P1; Lowermost Pliocene

Discontinuity M 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. Locally, there is some evidence of erosion that could indicate some short hiatus associate to Discontinuity M. Overall, the discontinuity has been interpreted as an important change in the deposition process. The overlying P1 sequence is highly reflective and made up of laterally extensive parallel seismic reflections up to 0.15 ms TWT in thickness and the distribution map of this sequence shows the main depocentre in the NE of the study area (Fig. 4).

The isochron map for the Seismic Unit P1 shows sedimentation focused broadly in an along-slope orientation with lobes fanning out to the Southwest (Fig. 4). Careful reconstruction of the regional palaeogeography in the Gulf of Cadiz gives clues to the likely origin of this seismic unit. Riaza and Marínez Del Olmo (1996) and Martínez del Olmo (2004) proposed that throughout the latest Miocene and Early Pliocene a down-slope system was supplying the region with sediment from the northeast. They suggest that there was an influx of clastic sedimentation across the northeast Gulf of Cadiz at this time which resulted in the deposition of the Guadiana Sands via down-slope (most likely turbiditic) processes. These sands have been identified in industry boreholes to the east of the study area (Riaza and Marínez Del Olmo, 1996). Based on this, and the distribution trends observed in the data, we can expect that this could be a distal turbiditic fan system, moving across the continental slope and being deflected basinwards. Systems with similar distribution patterns have been observed in the Peira Cava turbidite system in France (Amy et al., 2004; McCaffrey and Kneller, 2001). 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 down-slope deposits, and the 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 localized onlap relationships (Fig. 5). The proximity to the upper slope suggests that two discrete down-slope sedimentary systems were feeding this area – one minor down-slope system sourcing from the north and a large-scale down- and across-slope system sourcing from the northeast, which quickly dominated margin deposition (Fig. 6).

The Miocene–Pliocene boundary is generally accepted to be the time when the Strait of Gibraltar 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 when the MOW was established in the Gulf of Cadiz. Based on the present study, the seismic data shows little evidence of along-slope processes in the lowermost Pliocene. This is in agreement with interpretations from Hernández-Molina (2009), Hernández-Molina et al. (2009a), Llave et al. (2011) and Roque et al. (2012). Therefore, if exchange of water masses was occurring through the Strait at this time, they were insufficient to dominate margin deposition at a seismic scale.



**Figure 6.** 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 water currents is clear to see in along the upper slope and contourite channels. AD = Albufeira Drift; FEMD = Faro Elongate Mounded Drift; BDS = Bartolomeu-Dias Sheeted Drift; FSD = Faro Sheeted Drift; PH = Portimao High; GH = Guadalquivir High; PSD = Pliocene Sheeted Drift; MOW = Mediterranean Outflow Water.

### 6.1.2. 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 (Late Zanclean) (Llave et al., 2011) when the Gibraltar Gateway allowed for the exchange of water masses between the Atlantic Ocean and the Mediterranean Sea and exchange initiated. Such an oceanographic reorganization would have had a substantial effect on the depositional style of the margin, causing a change in dominant depositional processes.

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 through the Late Zanclean. Figure 6 maps the extent of down-slope vs. along-slope sediments, as 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 down-slope mass transport deposit accumulation. Their 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. Evidence for a contouritic origin for P2 include; (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 along-slope orientation; and (3) evidence for a highly cyclic nature of the sequence.

### 6.1.3. Seismic Unit P3; Upper Pliocene

One of the most subtle of the discontinuities along the Algarve Margin, the Upper Pliocene discontinuity (UPD) marks a change in sediment acoustic response of the unit with a move from high amplitude to semi-transparent seismic facies. The overlying Upper Pliocene sequence shows localized areas of high amplitude reflections in some areas, 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 mass transport processes were still active at this time.

The distribution of the seismic unit shows a largely sheeted morphology, orientated, but thinning along-slope. 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 considerably over the diapiric ridges and onlapping of seismic reflections onto the underlying UPD discontinuity. The local occurrence of high amplitude reflections can be linked to where diapir growth has affected bottom water flow and locally intensified it, resulting in localized patch drifts of coarser material (Fig. 3C). In the northwest of the study area there is still strong interbedding of down-slope (chaotic) and along-slope (parallel) seismic facies (Fig. 6) indicating that at this time, contourite deposition was not completely dominant.

### 6.1.4. Seismic Unit PQ: uppermost Pliocene–Lowermost Quaternary

The BQD marks a major change in the depositional style of the margin. Throughout the Pliocene, deposition has been 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 middle slope. Only a 'window' into the sequence is preserved basinwards (Figs. 3A and 4) and therefore it is difficult to be certain on 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 amplitudes and a move to discontinuities that are highly erosive in

nature and the drift begins to develop a more pronounced mounded morphology. These are characteristics of a high-energy contourite system. Thinning over the diapiric ridges in the east imply ongoing halokinesis, further intensifying the MOW at this time. As erosion dominated in the east of the study area (where erosional truncations are common in the unit), the west was a region of contourite deposition, where transport capacity of the bottom water fell as it exited the diapiric ridge province. Here, upslope progradation is evident, a feature common to contourite drift growth (Fig. 5) (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 this unit signifies a major period of repeated MOW intensifications and that the ongoing tectonic and diapiric movements were likely to be instrumental in the change to contourite-dominated system.

#### 6.1.5. Mid-upper 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). 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). This sedimentary record has been studied in great detail by Llave et al. (2007) and Roque et al. (2012) among others and is outside the scope of this paper. However, it forms a good contrast to the underlying Pliocene/Lower-Quaternary sheeted drift and contourite–turbidite mixed system. It is separated from the sheeted drift system by major discontinuities that are interpreted to be in response to tectonic readjustment of the margin. The mounded drift shows the development of a well-formed contourite moat along the middle slope, 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. Sheeted drift identification and characteristics

Seismic data almost always possesses uncertainty in the interpretation stage, with many possible outcomes (Sheriff and Geldart, 1995). Knowledge of the regional tectonic setting, palaeoceanographic set up of the margin and additional data such as bathymetric, petrophysical and sedimentological aid the clarification of the seismic data into a realistic and robust geological interpretation. The recognition of a contourite drifts on seismic is however still problematic, particularly where downslope processes are also ongoing since the seismic response is often similar (Shanmugam, 2012). Additional problems are encountered where the resolution of the seismic data is poor due to deep-penetrating low frequency acoustic data (as is commonly used in the petroleum industry) or by the use of older seismic data. 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 or aggradational stacking patterns (Faugères and Mulder, 2011; Faugères et al., 1999; 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 has proven more problematic, particularly in the sub-surface. Examples do exist 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.,

2009a) and around the Antarctic margin (Maldonado et al., 2003). The majority of these have been recognized, as with the Algarve Margin buried sheeted drift, due to their close relationship with turbidite and mounded contourite deposits respectively.

Here we examine in detail, the seismic characteristics of the sheeted drift found in the Lower Pliocene succession of the Algarve basin (Gulf of Cadiz) and discuss the close relationship between down-slope and along-slope processes at the beginning of drift formation. This is carried out at the scale of the drift to that of the seismofacies.

##### 6.2.1. Seismofacies-scale characteristics

Seismofacies are extremely variable in any sediment body and, in general, cannot solely be used to determine contouritic origin of a deposit. In the case of the Upper Pliocene drift within the Algarve basin 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 stark contrast to the chaotic down-slope sequence seen close to the continental slope (Fig. 3A). These seismic facies are seen to be interbedded in Seismic Units P2 and P3. A similar seismic facies relationship is observed in the Storegga slide complex and associated contourites offshore NW Europe, albeit on a larger scale (Solheim et al., 2005).

Contrasting Seismic Unit P1 with P2 illustrates the problem of distinguishing depositional processes from seismic facies alone. Locally, both sequences show very similar acoustic characteristics, and so they have been interpreted based on other observations on a larger scale.

##### 6.2.2. Depositional unit-scale characteristics

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 Gulf of Cadiz) show little to no progradation of seismic units. They observe that “gently downlapping reflections show only slight downcurrent progradation with either a basinward or landward oblique component”. In the Pliocene sheeted drift, this is certainly the case. Sequences identified across the drift are aggradational in nature. There is some evidence of minor progradation, including upslope progradation which is often an indication of contourite influenced sedimentation (Fig. 5). The intense interaction with down-slope processes to the east of this system (Fig. 3A) may disguise further prograding packages. Individual units are seen to downlap and are interpreted as prograding along-slope 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.

##### 6.2.3. Discontinuities and seismic unit identification

Regionally extensive erosional discontinuities are often important criteria for contourite identification. Previous work in this region has identified key discontinuities based on laterally continuous high amplitude reflections (Lopes et al., 2006; Maldonado et al., 1999; Marches et al., 2010). However, discontinuities in the study area are not always clearly erosive at a seismic scale or across a wide area, but can be due simply to a reorganization of the hydrodynamic set up of the margin. 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 (AI) between the under- and over-lying seismic packages may not necessarily be significant. The nature of high-energy contourite deposition (as is the case in the Gulf of Cadiz) is one of gradual waxing and waning flow. Erosional

discontinuities correlate to times of enhanced bottom water velocity, such as is seen in the uppermost Pliocene to Lowermost Quaternary in the study area. 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 diagenesis, or hard ground formation may form a remarkable seismic reflection, but the AI depends solely on the difference acoustic response of the over- and underlying sediment packages. As a result, many of the discontinuities identified in this detailed study 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 truncations, onlaps and downlap morphologies of the seismic reflections and not using solely the identification of laterally continuous high amplitude reflections.

#### 6.2.4. Drift-scale characteristics

Since contourite drift types are named on account of their external morphology (Faugères and Mulder, 2011; Faugères et al., 1999; McCave and Tucholke, 1986; Rebesco and Stow, 2001; Stow et al., 2002b), the drift identified in the Pliocene offshore the Algarve Margin can be classified as a sheeted drift within a mixed system. The overall morphology is that of consistent thickness and is mapped extending over an area of over 2000 km<sup>2</sup> (Fig. 6). 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 and is strikingly different to the overlying mounded elongated and separated drift (Faro-Albufeira drift).

Overall distribution of the drift is elongated in an NE–SW orientation, following the contours of the continental slope. 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 basin, the Pliocene oceanographic set-up is moderately well constrained (Hernández-Molina et al., 2011; Rogerson et al., 2012). It is well known that the opening of the Gibraltar Gateway occurred around the Miocene–Pliocene boundary (Nelson et al., 1999; Maldonado et al., 1999). Estimates for the full onset of the MOW are around the time of discontinuity Lower Pliocene Discontinuity (LPR) when upslope progradation begins to be seen in the seismic data. This provides good evidence for oceanographic conditions favourable to drift formation. Elongation of a sediment body along-slope can, when combined with knowledge of the palaeoceanographic set-up along a margin, aid the recognition of contourite sheeted drifts in the subsurface.

## 7. Implications

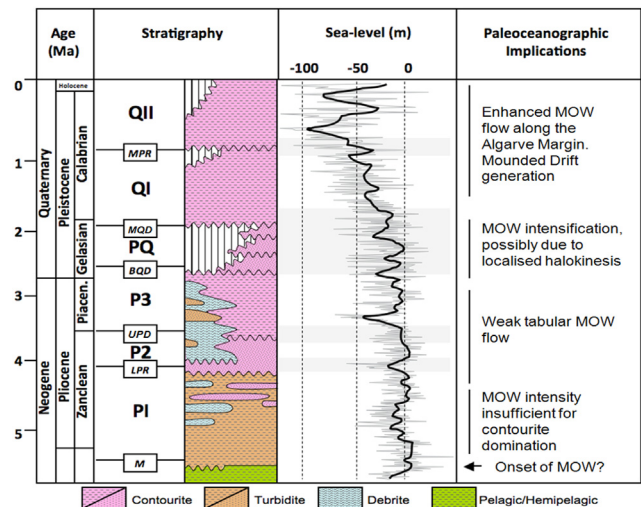
### 7.1. Palaeoceanographic implications

This mixed turbidite–contourite system and its acoustic response can tell us a great deal about the oceanographic evolution of the Algarve Margin. Authors have analysed the effects of relative sea level and global climatic changes on the MOW (Llave et al., 2006; Nelson et al., 1993; Stow et al., 2002a). Although it is challenging to completely isolate the climatic effects to the bottom water current, it appears that there is a basinwards shift of the dominant MOW core during times of lowstand due to increased density of the water mass (Llave et al., 2006). Therefore,

since the Algarve Margin is influenced by the upper core of the MOW, it would be expected that the most vigorous bottom waters are associated with highstand conditions. However, problems arise with this theory when the depositional sequences are compared to the global eustatic sea level curve (Miller et al., 2005). Figure 7 summarizes the relationship between sea level and the drift evolution. Neotectonics will further complicate this, and care must be taken to distinguish the two controls on bottom water velocity by looking at the margin-wide versus the localized response.

Within the Algarve Basin contourite succession, high cyclicity is observed in the acoustic data, indicating that there have been times of increased velocity and times of waning bottom water currents. Sea level fluctuations during the Pliocene and Quaternary are varied. Broad trends seen include a lowering of 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 palaeoceanographic implications of the Pliocene sequence.

Discontinuity M separates the Miocene from the lower Pliocene and signifies the end of the Messinian Salinity Crisis at 5.33 Ma (CIESM, 2008). Subsequent discontinuities represent times when bottom water velocities were enhanced sufficiently to cause widespread or localized erosion of the sea floor. Seismic Unit P2 represents the full onset of the Mediterranean Outflow Water 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 water velocities at this time and the deposition of a sandy-sheeted drift. Global sea-level trends (Fig. 7) show a relative high at this time (Miller et al., 2005). In addition, there is a strong influx of debrite deposits. 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 major tectonic events. Seismic Unit P3 has been interpreted as a time when relatively weak bottom water currents were in action over the drift. During this



**Figure 7.** The palaeoceanographic implications of each depositional sequence. Although some potential ties are seen between times of enhanced bottom water currents and eustatic sea level, there must be additional allogenic controls on the system. These are ties to alternative forcing such as tectonics and halokinesis. Eustasy curve from Miller et al. (2005).

time, there was a dramatic fall in sea level followed by a relative highstand (Fig. 7), 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 MOW 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 the Lower Core was intensified (outwith the study area). Seismic Unit PQ returns to high amplitude reflections with multiple erosional discontinuities. The section is partially absent due to erosion along much of the slope. 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, interpreted at 4th order glacio-eustatic cycles. In addition, the seismic indicates that this was a time of accelerated diapir growth to the east of the study area, and therefore the exceptionally vigorous bottom water currents can be attributed to the combination of high amplitude eustatic fluctuations enhanced by neotectonics (Fig. 6).

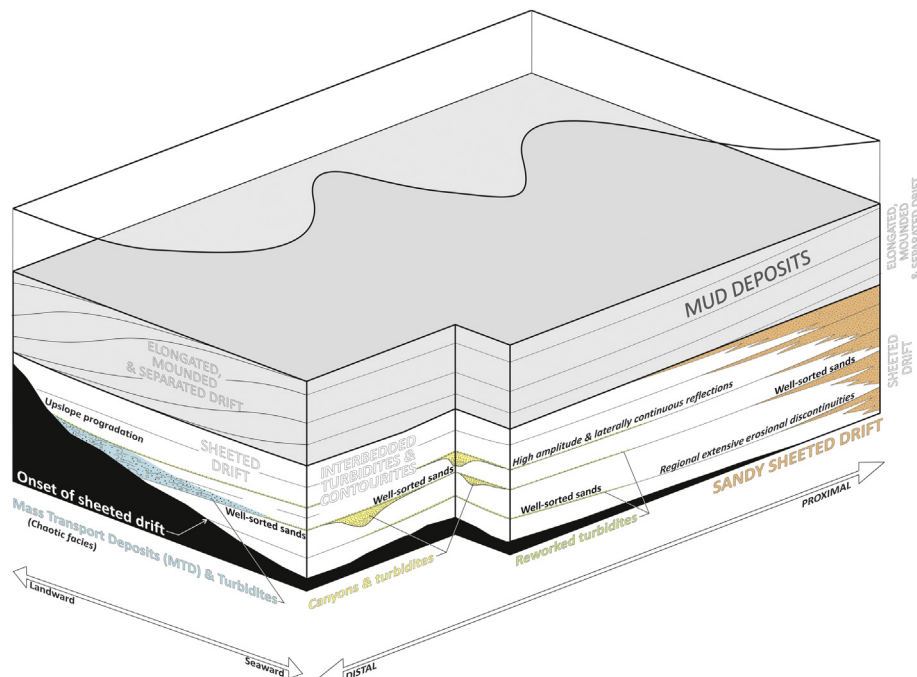
Three important conclusions from details palaeoceanographic studies can be made based on this work. Firstly, there does appear to be some link between eustasy and bottom water velocity, however it does not seem always be directly tied to the 3rd or 4th order cycles, but is more complex. This is in agreement with the findings of Rogerson et al. (2012). This 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. Secondly, the amplitude and duration of climatic and eustatic fluctuations cause differing responses to the contourite system. It is a highly complex relationship. Finally, the MOW itself has an important influence on the type of system that will develop and onset of processes that trigger turbulence in a bottom water mass can significantly alter the development of a contourite depositional system. The above observations show that seismic facies, acoustic amplitudes and seismic stratigraphic techniques can be used to analyse palaeoceanography on an along-slope and downslope mixed system, although all must be used to come to a robust conclusion.

## 7.2. Economic importance

Deep-water continental margins can provide all aspects of a petroleum system; mature source rocks, ample seal facies and trapping structures. These systems have therefore had growing economic interest in recent decades. The search for reservoir facies 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 economically viable reservoirs on account of their excellent lateral continuity, simple reservoir geometry, and well-sorted sediments (Weimer and Slatt, 2004). These lead to reservoirs that have high porosity and permeability values and high-rate, high-recovery reserves.

Mixed systems such as the Pliocene system offshore the Algarve Margin could provide a further reservoir facies for hydrocarbon exploration (Fig. 8). The interplay of down-slope clastic influx with strong along-slope current reworking can produce well-sorted sandy accumulations with excellent reservoir potential (Antich et al., 2005). Seismic Units P2 and PQ show promising signs of sand-rich contourite deposition. They are made up of high amplitude reflections when compared to other units and show 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 water reworking of clastic down-slope sediment holds the potential for excellent reservoir quality facies deposition (Mulder et al., 2008).

This has been demonstrated in the Santos Basin offshore Brazil (Bulhões et al., 2012; Viana et al., 1998; Viana and Rebesco, 2007). Here, sediment overflow from the shelf has been directly feeding into the bottom currents since the Oligocene. Additionally, there are downslope systems that are greatly modified where they are deposited in the path of vigorous bottom currents. The result is regions of high amplitude acoustic response and large-scale bed-forms where contourite sands are deposited. These deposits show some similarities to the Algarve Margin contourites of the Pliocene,



**Figure 8.** The Gulf of Cadiz contourite depositional system and mixed system provides a good example of many contourite sands. Upon further burial these could make excellent petroleum reservoirs. Sands accumulate within contourite channels or as broad sheet-like drifts.

albeit under a less aggressive current regime compared to that of the Santos Basin (which is largely transported away and leave only discrete patch drifts within a dominantly erosional regime). Along the Algarve Margin, Seismic Unit P2 shows seismic evidence of this process, with major sediment influx up-current (debrisites represented by chaotic seismic facies) resulting in the deposition of a sand-rich sheeted contourite drift downcurrent and basinwards (Fig. 5).

An alternative reservoir facies deposited in mixed systems could be winnowed turbidite deposits. Where down-slope processes, generally occurring on a timescale of minutes to hours, are influenced by longer-lasting (operating on a geological timescale) moderate bottom currents, the finer grain sizes may be removed by winnowing. The result is a sand-rich deposit exhibiting good sorting, porosity and permeability, and therefore good potential reservoir properties on burial. Examples of such deposits have been identified both on the sea-floor, for example in the Gulf of Mexico (Shanmugam and Muiola, 1982; Shanmugam, 2012), and in the subsurface as in the Campos basin (Mutti et al., 1980). If there is any minor onset of the MOW in the Lowermost Pliocene in the Algarve Basin (Seismic Unit P1), this mixed deposit could consist of clean sands and hold some reservoir potential.

A final mechanism for sand influx into a contourite system is outlined by Viana et al. (2007) as “downwelling of dense saline waters developing sand-rich channels”. This is a probably source of additional sediment influx to the modern Gulf of Cadiz Sand Sheet in the easternmost Gulf of Cadiz. Shelf spillover, downwelling of the MOW and bottom water current erosion contribute to the accumulation of sand across an area estimated to be 4000 km<sup>2</sup>. The contourite sand sheet is located at the exit of the Strait of Gibraltar across an area where the MOW speeds out and decelerates on exiting the confined Gibraltar Oceanic Gateway (Buitrago et al., 2001). Regions of bottom water acceleration through narrow conduits evidently provide a mechanism for impressive contourite sand accumulation and it may be this mechanism that resulted in the deposition of Seismic Unit PQ in the Algarve Basin on exiting a very active region of diapirism to the east of the study area.

The above examples highlight that where there is 1) sufficient transport capacity in a given bottom current for the transport and deposition of grain sizes >0.063 mm and 2) 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. Seismic data is a dominant source of information for the sub-surface and it is widely used to great effect in the hydrocarbon industry. Since misinterpretation of sheeted contourite deposits as turbidites has important implications for reservoir architecture and reservoir modelling, it is of great importance that contourite sand sheets are identifiable in geophysical data. As with turbidite sand identification, seismic reflection mapping and attribute analysis can give clues to the facies distribution, but care should be taken to also observe external and internal morphologies in addition to reconstructing the margin palaeoceanographic set up in order to fully determine the origin of a potential reservoir target.

## 8. Conclusions

A buried mixed contourite–turbidite system has been identified in the Pliocene succession in the Algarve basin. 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. The contourite drift was distinguished from turbidite deposits based on the acoustic character, distribution analysis and through careful palaeogeographic reconstruction. In

the earliest Pliocene, Seismic Unit P1 has been interpreted as a dominant down-slope (most likely turbidite or mass transport) system sourced mainly from the northeast. There is clear evidence of contourite reworking at 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 mass wasting deposits 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 water intensity; however upslope progradation shows that a mixed system was maintained. Above the Base Quaternary Discontinuity (ca. 2.6 Ma), highly erosive discontinuities and high amplitude seismic reflections are evidence of pronounced intensification of the MOW and of fully contourite-dominated slope.

As deepwater exploration becomes more and more important to meeting energy needs, it is important to further our understanding of these regions. Water masses circulation is particularly important in these deeper settings and as a result contourite deposits are very common and can hold the potential for good reservoirs, particularly where they are closely associated with a downslope system or other source of coarse clastic sediment. Where contourite–turbidite mixed systems can be identified in the subsurface, bottom water reworking holds the potential for excellent reservoir quality facies deposition. Misinterpretation of sheeted contourite deposits as turbidites has important implications for reservoir modelling and it is therefore of great importance that the interpreter has a good understanding of how to distinguish deepwater depositional processes using acoustic data. Key steps are to analyse seismic facies, sequence distribution and palaeo-margin set up prior to defining any depositional process.

## Acknowledgements

The study was funded through Institute of Petroleum Engineering Ali Danesh Scholarship. The study is related to the CONTOURIBER (CTM 2008-06399-C04/MAR) and MOWER (CTM2012-39599-C03-01) projects. Many thanks to TGS for allowing seismic sections to be published and to two reviewers who suggested modifications to improve the original manuscript.

## References

- Algarve-2, 1982. Arquivo Gabinete para a Prospecção e Exploração de Petróleo, no 21973-off/Exxon Esso. Final well report. Prospecção e Produção, S.A.R.L.
- Ambar, I., Howe, M., 1979. Observations of the Mediterranean outflow 1. Mixing in the Mediterranean outflow. *Deep-Sea Research Part A-Oceanographic Research Papers* 26, 535–554.
- Amy, L., McCaffrey, W., Kneller, B., Lomas, P., Lomas, S., 2004. The influence of a lateral basin-slope on the depositional patterns of natural and experimental turbidity currents. In: *Deep-water Sedimentation in the Alpine Basin of Se France: New Perspectives on the Gres D’annot and Related*, vol. 221, pp. 311–330.
- Antich, N., Buitrago, J., García Mojonero, C., Jiménez, A., Martínez del Olmo, W., 2005. Contourites: an unknown and excellent reservoir (Gulf of Cadiz, SW Spain). In: Martínez del Olmo, W. (Ed.), *Libro 25 Aniversario. Asociación de Geólogos y Geofísicos Españoles del Petróleo (AGGEP)*, Madrid, pp. 75–82.
- Baringer, M., Price, J., 1997. Mixing and spreading of the Mediterranean outflow. *Journal of Physical Oceanography* 27, 1654–1677.
- Baringer, M., Price, J., 1999. A review of the physical oceanography of the Mediterranean outflow. *Marine Geology* 155, 63–82.
- Borenas, K., Wahlin, A., Ambar, I., 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, 4195–4205.
- Bulhões, E., Freitas, J., Castro, M., Vasconcellos, C., Madeira, C., Carminatti, M., Mutti, E., 2012. The Interaction between Gravitational Flows and Contourite

- Currents in the Oligocene of the Santos Basin, Brazil. VIII Congreso Geológico de Espana. Geo-Temas, Oviedo, Spain, p. 539.
- Buitrago, J., García, C., Cajebread-Brow, J., Jiménez, A., y Martínez del Olmo, W., 2001. Contourites: Un excelente almacén casi desconocido (Golfo de Cádiz, SO de España). 1er Congreso Técnico Exploración y Producción REPSOL-YPF. Madrid, pp. 24–27.
- Cacho, I., Grimalt, J., Sierro, F., Shackleton, N., Canals, M., 2000. Evidence for enhanced Mediterranean thermohaline circulation during rapid climatic coolings. *Earth and Planetary Science Letters* 183, 417–429.
- Cataneanu, O., 2006. Principles of Sequence Stratigraphy. Elsevier, Amsterdam, p. 375.
- CIESM, 2008. The Messinian salinity Crisis from mega-deposits to microbiology—A consensus report. N° 33. In: Briand, F. (Ed.), CIESM Workshop Monographs, p. 168. Monaco.
- Evans, D., Stoker, M., Cramp, A., 1998. Geological processes on continental margins: sedimentation, mass-wasting and stability: an introduction. In: Stoker, M., Evans, D., Cramp, A. (Eds.), Geological Processes on Continental Margins: Sedimentation, Mass-wasting and Stability, Geological Society, Special Publication, London, pp. 1–4.
- Faugères, J.-C., Mulder, T., 2011. Contour currents and contourite drifts. In: Hüneke, H., Mulder, T. (Eds.), Deep Sea Sediments. Developments in Sedimentology.
- Faugères, J.-C., Mezerais, M., Stow, D., 1993. Contourite drifts types and their distribution in the North and South-Atlantic Ocean Basins. *Sedimentary Geology* 82, 189–203.
- Faugères, J.-C., Stow, D., 1993. Bottom-current-controlled sedimentation – a synthesis of the contourite problem. *Sedimentary Geology* 82, 287–297.
- Faugères, J.-C., Stow, D., Imbert, P., Viana, A., 1999. Seismic features diagnostic of contourite drifts. *Marine Geology*, 1–38.
- Flinch, J., Bally, A., Wu, S., 1996. Emplacement of a passive-margin evaporitic allochthon in the Betic Cordillera of Spain. *Geology* 24, 67–70.
- García Lafuente, J., Ruiz, J., 2007. The Gulf of Cadiz pelagic ecosystem: a review. *Progress in Oceanography* 74, 228–251.
- García, M., Hernández-Molina, F., Llave, E., Stow, D., Leon, R., Fernandez-Puga, M., del Rio, V., 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, 24–40.
- George, D., 2011. TGS-NOPEC's Portugal Survey Suspended, Oil and Gas Online.
- Gutscher, M., Malod, J., Rehault, J., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L., Spakman, W., 2002. Evidence for active subduction beneath Gibraltar. *Geology* 30, 1071–1074.
- Heezen, B., Hollister, C., Ruddiman, W., 1966. Shaping the continental rise by deep geostrophic contour currents. *Science* 152, 502–508.
- Hernández-Molina, F.J., Somoza, L., Vazquez, J.T., Lobo, F., Fernandez-Puga, M.C., Llave, E., Diaz-del Rio, V., 2002. Quaternary stratigraphic stacking patterns on the continental shelves of the southern Iberian Peninsula: their relationship with global climate and palaeoceanographic changes. *Quaternary International* 92, 5–23.
- Hernández-Molina, F.J., 2009. Los Sistemas Depositionales Contorníticos: ejemplos alrededor del Margen Ibérico. In: Ext Abstr Vol 6th Symp Atlantic Iberian Margin (MIA 09), Nuevas Contribuciones al Margen Ibérico Atlántico, 1–5 December 2009. University of Oviedo, pp. xxi–xxiv.
- Hernández-Molina, F., Llave, E., Stow, D., 2008. Continental slope contourites. In: Rebesco, M., Camerlenghi, A. (Eds.), Contourites. Developments in Sedimentology, pp. 379–408.
- Hernández-Molina, F., Llave, E., Stow, D., García, M., Somoza, L., Vazquez, J., Lobo, F., Maestro, A., del Rio, V., Leon, R., Medialdea, T., 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, 1420–1463.
- Hernández-Molina, F., Paterlini, M., Violante, R., Marshall, P., de Isasi, M., Somoza, L., Rebesco, M., 2009a. Contourite depositional system on the Argentine Slope: an exceptional record of the influence of Antarctic water masses. *Geology* 37, 507–510.
- Hernández-Molina, F.J., Matias, H., Llave, E., Stow, D.A.V., 2009b. Onset of contourite deposition in the Gulf of Cadiz: preliminary results. In: Ext Abstr Vol 6th Symp Atlantic Iberian Margin (MIA 09), Nuevas Contribuciones al Margen Ibérico Atlántico, 1–5 December 2009. University of Oviedo, pp. 277–280.
- Hernández-Molina, F., Serra, N., Stow, D., Llave, E., Ercilla, G., Van Rooij, D., 2011. Along-slope oceanographic processes and sedimentary products around the Iberian margin. *Geo-Marine Letters* 31, 315–341.
- Hernández-Molina, J., Llave, E., Somoza, L., Fernandez-Puga, M., Maestro, A., Leon, R., Medialdea, T., Barnolas, A., García, M., del Rio, V., Fernandez-Salas, L., Vazquez, J., Lobo, F., Dias, J., Rodero, J., Gardner, J., 2003. Looking for clues to palaeoceanographic imprints: a diagnosis of the Gulf of Cadiz contourite depositional systems. *Geology* 31, 19–22.
- Howe, J., 2008. Methods for contourite research. In: Rebesco, M., Camerlenghi, A. (Eds.), Contourites. Developments in Sedimentology, pp. 19–34.
- Howe, M., 1982. The Mediterranean water outflow in the Gulf of Cadiz. *Oceanography and Marine Biology* 20, 37–64.
- Hsü, K., Ryan, W., Cita, M., 1973. Late Miocene desiccation of Mediterranean. *Nature* 242, 240–244.
- Hüneke, H., Stow, D., 2008. Identification of Ancient contourites: problems and palaeoceanographic significance. In: Rebesco, M., Camerlenghi, A. (Eds.), Contourites. Developments in Sedimentology, pp. 323–344.
- Khelifi, N., Sarnthein, M., Andersen, N., Blanz, T., Frank, M., Garbe-Schonberg, D., Haley, B., Stumpf, R., Weinelt, M., 2009. A major and long-term Pliocene intensification of the Mediterranean outflow, 3.5–3.3 Ma ago. *Geology* 37, 811–814.
- Llave, E., Hernández-Molina, F., Somoza, L., Diaz-del-Rio, V., Stow, D., Maestro, A., Dias, J., 2001. Seismic stacking pattern of the Faro-Albufeira contourite system (Gulf of Cadiz): a Quaternary record of palaeoceanographic and tectonic influences. *Marine Geophysical Researches* 22, 487–508.
- Llave, E., Hernández-Molina, F., Stow, D., Fernandez-Puga, M., García, M., Vasquez, J., Maestro, A., Somoza, L., Del Rio, V., 2007. 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, 379–394.
- Llave, E., Matias, H., Hernández-Molina, F., Ercilla, G., Stow, D., Medialdea, T., 2011. Pliocene–Quaternary contourites along the northern Gulf of Cadiz margin: sedimentary stacking pattern and regional distribution. *Geo-Marine Letters* 31, 377–390.
- Llave, E., Matias, H., Hernández-Molina, F., Ercilla, G., Stow, D., 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., Schönfeld, J., Hernández-Molina, F., Mulder, T., Somoza, L., del Rio, V., 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, 241–262.
- Locker, S., Laine, E., 1992. Palaeogene–Neogene depositional history of the middle U.S. Atlantic continental rise: mixed turbidite and contourite depositional systems. *Marine Geology* 103, 137–164.
- Lopes, F., Cunha, P., Le Gall, B., 2006. Cenozoic seismic stratigraphy and tectonic evolution of the Algarve margin (offshore Portugal, southwestern Iberian Peninsula). *Marine Geology* 231, 1–36.
- Loseth, H., Gading, M., Wensaas, L., 2009. Hydrocarbon leakage interpreted on seismic data. *Marine and Petroleum Geology* 26, 1304–1319.
- Maldonado, A., Barnolas, A., Bohoyo, F., Galindo-Zaldívar, J., Hernández-Molina, J., Lobo, F., Rodriguez-Fernandez, J., Somoza, L., 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, 187–221.
- Maldonado, A., Nelson, C., 1999. Interaction of tectonic and depositional processes that control the evolution of the Iberian Gulf of Cadiz margin. *Marine Geology* 155, 217–242.
- Maldonado, A., Somoza, L., Pallares, L., 1999. The Betic orogen and the Iberian–African boundary in the Gulf of Cadiz: geological evolution (central North Atlantic). *Marine Geology* 155, 9–43.
- Marches, E., Mulder, T., Gonthier, E., Cremer, M., Hanquiez, V., Garland, T., 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, 81–94.
- Martínez del Olmo, W., 2004. La exploración de hidrocarburos en el Terciario de España. *Boletín Geológico y Minero* 115, 411–426.
- Masson, D., 2001. Sedimentary processes shaping the eastern slope of the Faeroe-Shetland Channel. *Continental Shelf Research* 21, 825–857.
- McCaffrey, W., 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, 971–988.
- McCave, I., Tucholke, B., 1986. Deep current-controlled sedimentation in the western North Atlantic. In: Vogt, P., Tucholke, B. (Eds.), The Geology of North America, the Western North Atlantic Region. Decade of North American Geology. Geological Society of America, Boulder, pp. 451–468.
- Medialdea, T., Somoza, L., Pinheiro, L., Fernandez-Puga, M., Vazquez, J., Leon, R., Ivanov, M., Magalhaes, V., Diaz-del-Rio, V., Vegas, R., 2009. Tectonics and mud volcano development in the Gulf of Cadiz. *Marine Geology* 261, 48–63.
- Medialdea, T., Vegas, R., Somoza, L., Vazquez, J., Maldonado, A., Diaz-Del-Rio, V., Maestro, A., Cordoba, D., 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, 173–198.
- Miller, K., Kominz, M., Browning, J., Wright, J., Mountain, G., Katz, M., Sugarman, P., Cramer, B., Christie-Blick, N., Pekar, S., 2005. The Phanerozoic record of global sea-level change. *Science* 310, 1293–1298.
- Moraes, M., Maciel, W., Braga, M., Viana, A., 2007. Bottom-current reworked Palaeocene–Eocene deep-water reservoirs of the Campos Basin, Brazil. In: Viana, A., Rebesco, M. (Eds.), Economic and Palaeoceanographic Significance of Contourite Deposits, Geological Society, Special Publications, London, pp. 81–94.
- Mulder, T., Voisset, M., Lecroart, P., Le Dren, E., Gonthier, E., Hanquiez, V., Faugères, J.-C., 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., Morel, J., 2003. The Gulf of Cadiz: an unstable giant contourite levee. *Geo-Marine Letters* 23, 7–18.
- Mulder, T., Faugères, J.-C., Gonthier, E., 2008. Mixed turbidite–contourite systems. In: Rebesco, M., Camerlenghi, A. (Eds.), Contourites. Developments in Sedimentology, pp. 435–456.
- Mutti, E., Barros, M., Possato, S., 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. International Association of Sedimentologist, p. 114.

- Nelson, C., Baraza, J., Maldonado, A., 1993. Mediterranean undercurrent sandy contourites, Gulf of Cadiz, Spain. *Sedimentary Geology* 82, 103–131.
- Nelson, C., Maldonado, A., 1999. The Cadiz margin study off Spain: an introduction. *Marine Geology* 155, 3–8.
- Nelson, C.H., Baraza, J., Maldonado, A., Rodero, J., Escutia, C., 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, 99–129.
- Nielsen, J., 1912. *Hydrography of the Mediterranean and Adjacent Waters*, Copenhagen.
- Nielsen, T., Kuijpers, A., Knutz, P., 2008. Seismic expression of contourite depositional systems. In: Rebesco, M., Camerlenghi, A. (Eds.), *Contourites. Developments in Sedimentology*, pp. 301–322.
- Preu, B., Hernández-Molina, F., Violante, R., Piola, A., Paterlini, C., Schwenk, T., Voigt, I., Krastel, S., Speiss, V., 2013. Morphosedimentary and hydrographic features of the northern Argentine margin: the interplay between erosive, depositional and gravitational processes and its conceptual implications. *Deep-Sea Research I* 75, 157–174.
- Raddatz, J., Rüggeberg, A., Margreth, S., Dullo, W.-C., Party, I.E.S., 2011. Palaeoenvironmental reconstruction of Challenger Mound initiation in the Porcupine Seabight, NE Atlantic. *Marine Geology* 282, 79–90.
- Rebesco, M., 2005. Contourites. In: Selley, R., Cocks, L., Plimer, I. (Eds.), *Encyclopedia of Geology*. Elsevier, Oxford, pp. 513–527.
- Rebesco, M., Camerlenghi, A., 2008. Contourites. *Developments in Sedimentology*, Amsterdam.
- Rebesco, M., Pudsey, C., Canals, M., Camerlenghi, A., Baker, P., Estrada, F., Giorgetti, A., 2002. Sediment drifts and deep-sea channel systems, Antarctic Peninsula Pacific Margin. In: Stow, D., Pudsey, C., Howe, J., Faugères, J.-C., Viana, A.R. (Eds.), *Deep-Water Contourite Systems: Modern Drifts and Ancient Series*, Seismic and Sedimentary Characteristics. Geological Society, London, pp. 353–371.
- Rebesco, M., Stow, D., 2001. Seismic expression on contourites and related deposits: a preface. *Marine Geophysical Research* 22, 303–308.
- Riaza, C., Marín del Olmo, W., 1996. Depositional model of the Guadalquivir-Gulf of Cadiz Tertiary Basin. In: Friend, P., Dabrio, C. (Eds.), *Tertiary Basins of Spain: the Stratigraphic Record of Crustal Kinematics*. Cambridge University Press, Cambridge, pp. 330–338.
- Roest, W., 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, 613–616.
- Rogerson, M., Rohling, E., Bigg, G., Ramirez, J., 2012. Palaeoceanography of the Atlantic-Mediterranean exchange: overview and first quantitative assessment of climate forcing. *Reviews of Geophysics* 50.
- Rogerson, M., Rohling, E., Weaver, P., Murray, J., 2005. Glacial to interglacial changes in the settling depth of the Mediterranean Outflow plume. *Palaeoceanography* 20.
- Roque, C., Duarte, H., Terrinha, P., Valadares, V., Noiva, J., Cachao, M., Ferreira, J., Legoinha, P., Zitellini, N., 2012. Pliocene and Quaternary depositional model of the Algarve margin contourite drifts (Gulf of Cadiz, SW Iberia): seismic architecture, tectonic control and palaeoceanographic insights. *Marine Geology* 303, 42–62.
- Rosenbaum, G., Lister, G., Duboz, C., 2002. Reconstruction of the tectonic evolution of the western Mediterranean since the Oligocene. In: Rosenbaum, G., Lister, G. (Eds.), *Reconstruction of the Evolution of the Alpine-Himalayan Orogen*. Journal of the Virtual Explorer. Paper 6.
- Royden, L., 1993. Evolution of retreating subduction boundaries formed during continental collision. *Tectonics* 12, 629–638.
- Serra, N., Ambar, I., Boutov, D., 2010. Surface expression of Mediterranean Water dipoles and their contribution to the shelf/slope-open ocean exchange. *Ocean Science* 6, 191–209.
- Shanmugam, G., 2006. Deep-water bottom currents. In: Shanmugam, G. (Ed.), *Deep-Water Processes and Facies Models; Implications for Sandstone Petroleum Reservoirs*, Handbook of Petroleum Exploration and Production, vol. 5, pp. 85–139.
- Shanmugam, G., 2012. New perspectives on deep-water sandstones. In: Shanmugam, G. (Ed.), *New Perspectives on Deep-Water Sandstones*, Handbook of Petroleum Exploration and Production, vol. 9, pp. 129–219.
- Shanmugam, G., Muiola, R., 1982. Eustatic control of deep-sea reservoir facies. *AAPG Bulletin-American Association of Petroleum Geologists* 66, 629–630.
- Shannon, P., Stoker, M., Praeg, D., van Weering, T., de Haas, H., Nielsen, T., Dahlgren, K., Hjelstuen, B., 2005. Sequence stratigraphic analysis in deep-water, underfilled NW European passive margin basins. *Marine and Petroleum Geology* 22, 1185–1200.
- Sheriff, R., Geldart, L., 1995. *Exploration Seismology*. Cambridge University Press, Cambridge.
- Solheim, A., Berg, K., Forsberg, C.F., Bryn, P., 2005. The Storegga Slide complex: repetitive large scale sliding with similar cause and development. *Marine and Petroleum Geology* 22, 97–107.
- Somoza, L., Díaz-del-Río, 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., 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, 153–176.
- Srivastava, S., Schouten, H., Roest, W., Klitgord, K., Kovacs, L., Verhoef, J., Macnab, R., 1990. Iberian plate kinematics – a jumping plate boundary between Eurasia and Africa. *Nature* 344, 756–759.
- Stoker, M., Akhurst, M., Howe, J., Stow, D., 1998. Sediment drifts and contourites on the continental margin off northwest Britain. *Sedimentary Geology* 115, 33–51.
- Stow, D., Faugères, J.-C., Gonthier, E., Cremer, M., Llave, E., Hernández-Molina, F., Somoza, L., Díaz-Del-Río, V., 2002a. Faro-albufeira Drift Complex, Northern Gulf of Cadiz. In: Geological Society, London, *Memoirs*, pp. 137–154.
- Stow, D., Faugères, J.-C., Howe, J., Pudsey, C., Viana, A., 2002b. Bottom currents, contourites and deep-sea sediment drifts: current state-of-the-art. In: Stow, D., Pudsey, C., Howe, J., Faugères, J.-C., Viana, A. (Eds.), *Deep-water Contourite Systems: Modern Drifts and Ancient Series*, Seismic and Sedimentary Characteristics. Geological Society, London, pp. 7–20.
- Stow, D., Hernández-Molina, F.E.L., Sayago-Gil, M., Díaz del Río, V., Branson, A., 2009. Bedform-velocity matrix: the estimation of bottom current velocity from bedform observations. *Geology* 37, 327–330.
- Stow, D., Mayall, M., 2000. Deep-water sedimentary systems: new models for the 21st century. *Marine and Petroleum Geology* 17, 125–135.
- Surlyk, F., Lykke-Andersen, H., 2007. Contourite drifts, moats and channels in the Upper Cretaceous chalk of the Danish Basin. *Sedimentology* 54, 405–422.
- TGS, 2005. PD00: non-exclusive 2D Survey, TGS online data zone. [http://www.tgsnopec.com/specsheets/PD-00\\_Spec.pdf](http://www.tgsnopec.com/specsheets/PD-00_Spec.pdf).
- Toucanne, S., Mulder, T., Schönfeld, J., Hanquiez, V., Gonthier, E., Duprat, J., Cremer, M., Zaragosi, S., 2007. Contourites of the Gulf of Cadiz: a high-resolution record of the palaeocirculation of the Mediterranean outflow water during the last 50,000 years. *Palaeogeography, Palaeoclimatology, Palaeoecology* 246, 354–366.
- Van Rooij, D., Iglesias, J., Hernández-Molina, F., Ercilla, G., Gomez-Ballesteros, M., Casas, D., Llave, E., De Hauwere, A., García-Gil, S., Acosta, J., Henriot, 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.
- Viana, A., 2001. Seismic expression of shallow- to deep-water contourites along the south-eastern Brazilian margin. *Marine Geophysical Researches* 22, 509–521.
- Viana, A., Almeida Jr., W., Nunes, M., Bulhões, E., 2007. The economic importance of contourites. In: Viana, A., Rebesco, M. (Eds.), *Economic and Palaeoceanographic Significance of Contourite Deposits*. Geological Society, London, pp. 1–23.
- Viana, A., Faugères, J.-C., Stow, D., 1998. Bottom-current-controlled sand deposits – a review of modern shallow- to deep-water environments. *Sedimentary Geology* 115, 53–80.
- Viana, A., Hercos, C., WD Jr., A., Magalhães, J., Andrade, S., 2002. Evidence of bottom current influence on the Neogene to Quaternary sedimentation along the northern Campos Slope, SW Atlantic Margin. In: Stow, D., Pudsey, C., Howe, J., Faugères, J.-C., Viana, A. (Eds.), *Deep-water Contourite Systems: Modern Drifts and Ancient Series*, Seismic and Sedimentary Characteristics. Geological Society, London, pp. 249–259.
- Viana, A., Rebesco, M., 2007. Economic and Palaeoceanographic Significance of Contourite Deposits. Geological Society, London.
- Voelker, A., Lebreiro, S., Schönfeld, J., Cacho, I., Erlenkeuser, H., 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.
- Weimer, P., Slatt, R., 2004. *Petroleum Systems of Deepwater Settings*. Society of Exploration Geophysicists and European Association of Geoscientists and Engineers.
- Zenk, W., 1970. On the temperature and salinity structure of Mediterranean-Water in northeast-Atlantic. *Deep-Sea Research* 17, 627–630.
- Zitellini, N., Gracia, E., Matias, L., Terrinha, P., Abreu, M., DeAlteriis, G., Henriot, J., Danobeitia, J., Masson, D., Mulder, T., Ramella, R., Somoza, L., Diez, S., 2009. The quest for the Africa–Eurasia plate boundary west of the Strait of Gibraltar. *Earth and Planetary Science Letters* 280, 13–50.