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ORIGINAL RESEARCH PAPER

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

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Abstract Contourite deposits in the central sector of the middle slope of the Gulf of Cadiz have been studied using a comprehensive acoustic, seismic and core database. Buried, mounded, elongated and separated drifts developed under the influence of the lower core of the Mediterranean Outflow Water are preserved in the sedimentary record. These are characterised by depositional features in an area where strong tectonic and erosive processes are now dominant. The general stacking pattern of the depositional system is mainly influenced by climatic changes through the Quaternary, whereas changes in the depositional style observed in two, buried, mounded drifts, the Guadalquivir and Huelva Drifts, are evidence of a tectonic control. In the western Guadalquivir Drift, the onset of the sheeted drift construction (aggrading QII unit) above a mounded drift (prograding QI unit) resulted from a new Lower Mediterranean Core Water hydrodynamic regime. This change is correlated with a tectonic event coeval with the Mid Pleistocene Revolution (MPR) discontinuity that produced new irregularities of the seafloor during the Mid- to Late-Pleistocene. Changes in the Huelva Drift from a mounded to a sheeted drift geometry during the Late-Pleistocene, and from a prograding drift (QI and most part of QII) to an aggrading one (upper seismic unit of QII), highlight a new change in oceanographic conditions. This depositional and then oceanographic change is associated with a tectonic event, coeval with the Marine Isotope Stage (MIS) 6 discontinuity, in which a redistribution of the diapiric ridges led to the development of new local gateways, three principal branches of the Mediterranean Lower Core Water, and associated contourite channels. As a result, these buried contourite drifts hold a key palaeoceanographic record of the evolution of Mediterranean Lower Core Water, influenced by both neotectonic activity and climatic changes during the Quaternary. This study is an example of how contourite deposits and erosive elements in the marine environment can provide evidence for the reconstruction of palaeoceanographic and recent tectonic changes.

Keywords Contourite deposits · Gulf of Cadiz · Mediterranean Outflow Water · Quaternary · Seismic stratigraphy · Neotectonics · Diapirism · Palaeoceanography

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Introduction

Contourite drifts are common depositional features in present-day ocean basins, especially along continental margins, where they occur as large sedimentary bodies. Several classifications have recently been proposed for contourite drifts, based mainly on their morphological, sedimentological and seismic characteristics (e.g., McCave and Tucholke 1986; Faugères and Stow 1993; Faugères et al. 1993, 1999; Gao et al. 1998; Rebesco and Stow 2001; Stow et al. 1986, 2002; Rebesco 2005). The close relation between drifts and regional oceanographic and physiographic conditions makes the specific characteristics of the drifts an important tool for deducing the flow pathways of the principal water masses responsible for their development. Therefore, buried contourite drifts in a marine basin provide clues for the reconstruction of palaeoceanographic conditions (Hernández-Molina et al. 2006a).

On the continental margin of the Gulf of Cadiz, eastern Atlantic Ocean (Fig. 1), an extensive contourite depositional system (CDS) has developed from the Messinian to the present, comprising different depositional and erosive features (Nelson et al. 1993; Buitrago et al. 2001; Hernández-Molina et al. 2003; Llave 2003; Llave et al. 2007). Although there have been several studies of these contourites, these have generally focused along the northern continental slope, especially on the Faro or Faro-Albufeira Drift (e.g., Vanney and Mougenot 1981; Gonthier et al. 1984; Mougenot 1988; Faugères et al. 1985; Stow et al. 1986). The onset of drift construction is indicated by a marked basal discontinuity that resulted from a new hydrodynamic regime after the opening of the Straits of Gibraltar, in which the Mediterranean Outflow Water (MOW) began to flow westwards through the Gibraltar Gateway. The subsequent onset of marked northward progradation of Faro Drift deposits began around 3 to 2.4 Ma (Late Pliocene) (Faugères et al. 1985).

This article presents new, detailed results of the central area of the middle slope (Sector 3 of the Contourite Depositional System defined by Hernández-Molina et al. 2003) where two buried mounded elongated and separated drifts are identified in an area where erosive processes are currently dominant (Nelson et al. 1993, 1999; García, 2002; Hernández-Molina et al. 2003, 2006b; Llave et al. 2007). The singularity of the newly identified mounded contourite deposits is that they are preserved in the sedimentary record and, although they are presently inactive, they do provide an important record of the main palaeoceanographic and tectonic influences on contourite development in the Gulf of Cadiz during the Quaternary.

Geological framework

The study area is located in the central zone of the middle slope of the Gulf of Cadiz, between 36°15′ to 36°45′ N and 8° to 6°45′ W (Fig. 1), and overlies the African-Eurasian plate boundary. Kinematic studies have shown that this area has been subjected to a general N–S to NNE–SSW convergence between the main African and Eurasian plates, at least since the Early Oligocene (Srivastava et al. 1990; Maldonado et al. 1999), with a modern slow oblique convergence (Nocquet and Clais 2004). Since the Tortonian (10 Ma) a structural reorganization, characterised by extensional collapse of the orogenic front produced remobilisation of the Cadiz Allochtonous Unit (Medialdea et al. 2004). This unit is characterised by both downslope gravity gliding and tectonic compression westward from the front of the deformed wedge. Post-Tortonian deformation produced NW–SE directed extensional structures and NE-verging thrusts in the northern middle slope of the Gulf of Cadiz (Fernandez-Puga et al. 2007). Both types of structures are rooted in Miocene marls and Triassic salts. The migration of these marls and evaporite units drove diapiric processes, manifested in isolated dome-shaped morphologies and diapiric ridge systems, as well as areas with high subsidence rates (Maestro et al. 2003). Neogene-Quaternary tectonic activity has resulted in a structurally very complex continental margin with a morphology where the occurrence and reactivation of the Cadiz Allochthonous Unit in the central sector of the Gulf of Cadiz has produced: (a) a marked fan-like margin geometry, with a concave-upward bulge over the middle slope and convex-upward isobaths in the lower slope (Flinch et al. 1996; Torelli et al. 1997; Medialdea et al. 2004); (b) fault reactivation (Maestro et al. 1998; Jané 2007); (c) compressive and extensional structures coherent with the main stress regime (Flinch et al. 1996; Torelli et al. 1997; Medialdea et al. 2004); (d) the development of an important diapiric regime across the margin (Medialdea et al. 2004; Fernández-Puga 2004) and (e) fluid migration and mud volcanoes generation (Kenyon et al. 2000; Diaz-del-Río et al. 2003; Somoza et al. 2003; Maestro et al. 2003; Fernández-Puga et al. 2007; Gonzalez et al. 2007; Martin-Puertas et al. 2007).

Oceanographic setting

Circulation in the Gulf of Cadiz has been characterised by exchange of water masses through the Gibraltar Gateway (Fig. 1a) since its opening at the end of the Messinian. This exchange involves a warm and highly saline current known as Mediterranean Outflow Water (MOW) flowing near the bottom, beneath a turbulent, less saline, cool-water mass

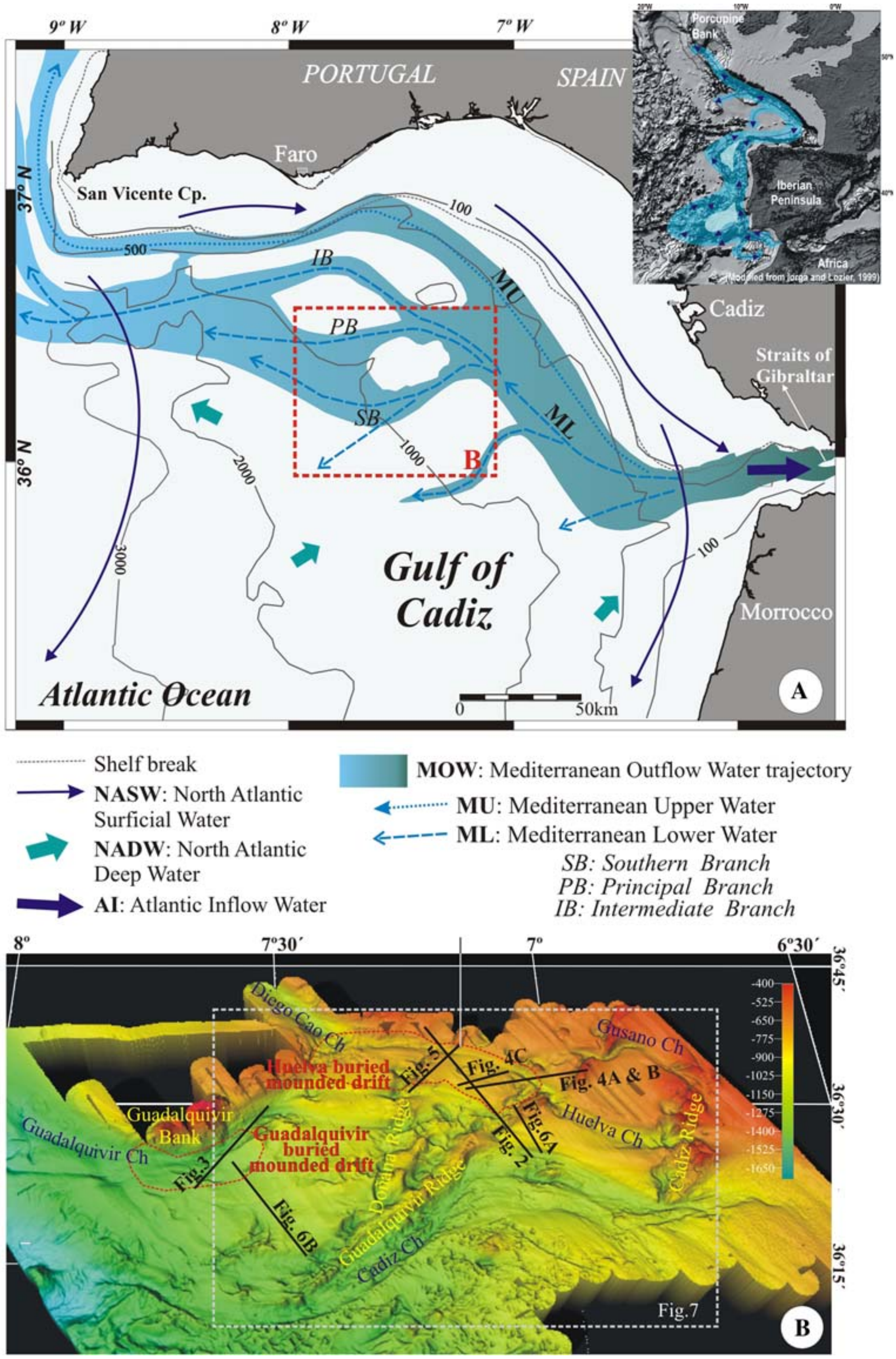


Fig. 1 (**a**) Location of the study area in the Gulf of Cadiz with a regional bathymetric map indicating the general circulation patterns of *Mediterranean Outflow Water*, within the general circulation in the NE Atlantic Ocean (Iorga and Lozier 1999). (**b**) Swath bathymetry of the central sector of the middle slope (Channel & Ridge Sector), showing the main contourite channels and the main diapiric ridge, with a NNE–SSW direction. This map was obtained using the Simrad EM12S-120 system during the TASYO-2000 cruise. The location of the *buried contourite deposits* as well as the location of the seismic profiles used in this paper is indicated on it

known as Atlantic Inflow Water, which reaches depths of 40–200 m (Gascard and Richez 1985). Although we present here the general setting of the Mediterranean Outflow Water, a complete summary of the water mass characteristics and distribution in the Gulf of Cadiz was published by Hernández-Molina et al. (2006) based on previous studies by Madelain (1970), Kenyon and Belderson (1973), Meliéres (1974), Zenk (1975) and Ochoa and Bray (1991). After passing the Straits of Gibraltar, the Mediterranean Outflow Water flows to the northwest along the middle slope due to the influence of the Coriolis force and above the North Atlantic Deep Water (e.g. Madelain 1970; Zenk

1975; Ambar and Howe 1979; Ochoa and Bray 1991; Baringer and Price 1999; Serra 2004; Ambar and Serra 2007). As it moves westward, Mediterranean Outflow Water registers a drop in temperature, salinity and velocity, and divides into two main cores (Madelain 1970; Kenyon and Belderson 1973; Melières 1974; Zenk 1975; Ambar and Howe 1979; Ochoa and Bray 1991; Ambar et al. 1999; Nelson et al. 1993, 1999; Hernández-Molina et al. 2003) (Fig. 1a): (a) Mediterranean Upper Core Water, flowing at the base of the upper slope (500–800 m deep) towards Cape San Vicente and (b) Mediterranean Lower Core Water, which constitutes the Mediterranean Outflow Water's principal nucleus, at depths of 750–1,200 m. The interaction of this Lower Core with the irregular slope morphology induces a further division into three minor branches (Fig. 1a): (1) the Intermediate Branch, which moves northwestward through the Diego Cao Channel; (2) the Principal Branch, which flows towards the southwest through the Guadalquivir Channel, and (3) the Southern Branch, which follows a steep valley towards the southwest along the Cadiz Channel.

Regional stratigraphy

A regional seismic stratigraphic analysis was carried out by Llave et al. (2001, 2007) and Hernández Molina et al. (2002), and was used to correlate the seismic units differentiated in the present study in the central area of the middle slope of the Gulf of Cadiz. The seismic units represent depositional sequences at three different scales hereinafter referred for simplicity as *depositional sequences*, *depositional units*, and *subunits* (Table 1). Two depositional sequences have been identified in the Quaternary sedimentary record: QI and QII. Based on nannofossil biostratigraphic studies carried out by Llave (2003) and Llave et al. (2004a, 2007) the age of the main discontinuities differentiated within the Quaternary contourite record were determined: the base was dated at around 1.8 Ma, and the MPR discontinuity that separated QI and QII was dated at about 900 ky. The "Mid Pleistocene Revolution" (MPR) discontinuity is considered an important change in the climatic trend that occurred 900–920 ka (Shackleton and Opdyke 1973; Shackleton et al. 1990; Berger and Wefer 1992; Berger et al. 1994; Muldelsee and Stattegger 1997; Howard 1997; Paillard 1998; Loutre and Berger 1999). Oxygen isotope records of planktonic foraminifera and the occurrence of ice-rafted debris (IRD) analysed provided a Late Pleistocene age for the youngest depositional unit H (Mulder et al. 2002; Llave et al. 2004b, 2006). The previous analyses demonstrated that these depositional sequences were formed during the regression and lowstand of sea level, and the main discontinuities are associated with regional erosive stages that occurred during glacial stages. Further details of the nature and subdivision of these sequences is provided in this paper.

Main tectonic and erosive features of the central sector of the middle slope

The central sector of the middle slope is crossed by three main NE-trending diapiric ridges, including the Doñana, Guadalquivir and Cadiz, and the Guadalquivir Bank basement high (Figs. 1b and 2) (Hernández-Molina et al. 2003). The northern ridge is known as the Doñana Diapiric Ridge and it is the closest to the Guadalquivir Bank, at water depths of 500–1,100 m (Figs. 1b and 2). The ridge outcrops in restricted areas as isolated bodies and is associated with several active mud volcanoes (Fernández-Puga 2004). The Guadalquivir Diapiric Ridge is an elongated and highly deformed ridge situated at 300–1,100 m water depth (Figs. 1b and 2) formed by intrusion of a large diapiric mass. It has undergone several episodes of activity from the Middle Miocene to the present, deforming and cutting the seafloor, as well as the Cadiz Diapiric Ridge (Maestro et al. 2003; Fernández-Puga 2004), which is around 43 km long, up to 14 km wide, and penetrates the seafloor with a N–S trend at 400–800 m water depth (Fig. 1b).

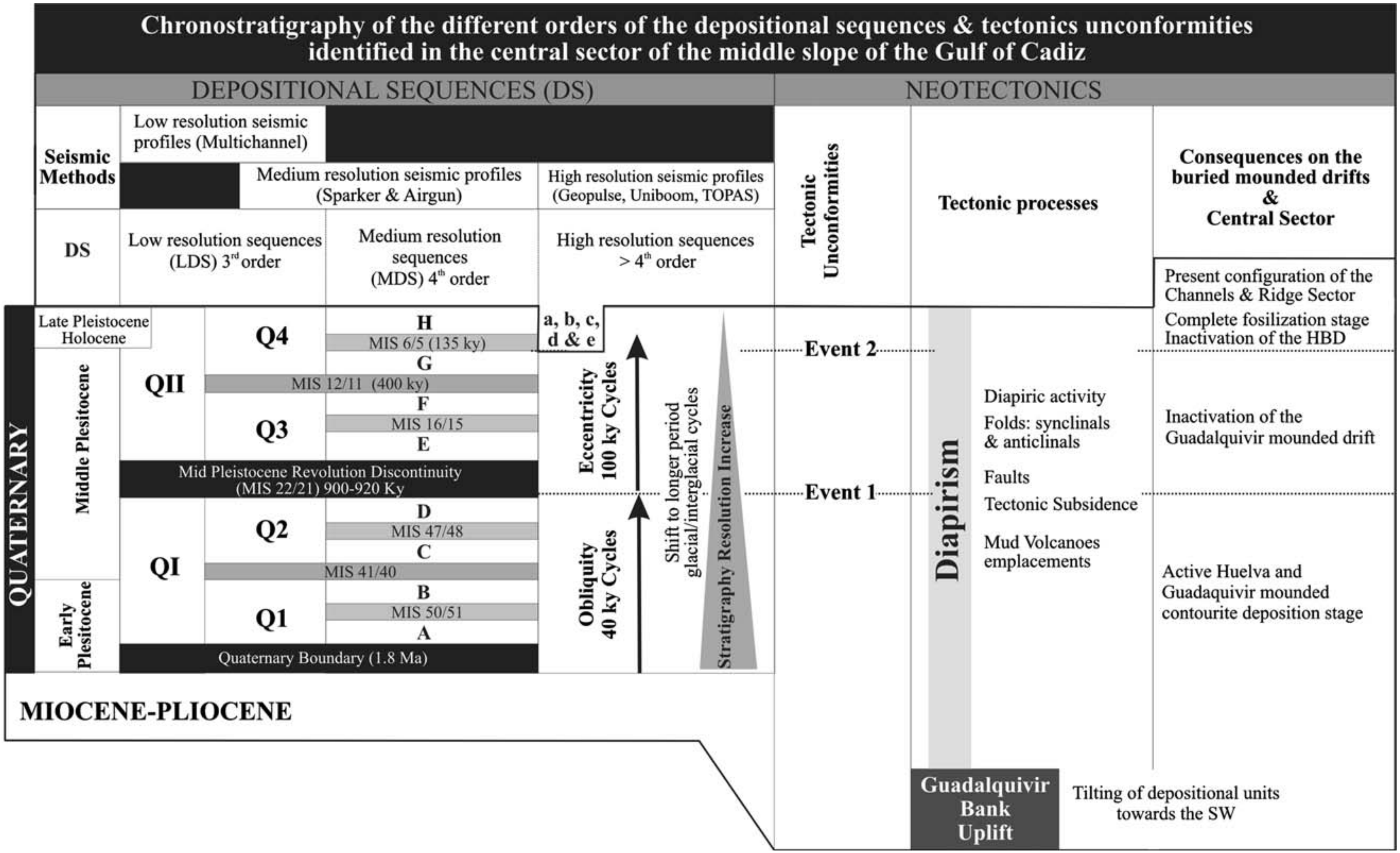
The Guadalquivir Bank represents a structural basement high comprising Paleozoic and Mesozoic rocks of the Iberian margin (Medialdea et al. 2004; Vegas et al. 2004). It is located in a water depth of around 300–500 m and covers an area measuring 18 km by 12 km (Fig. 1b).

The main erosive features that characterized the sea bottom of the study area are represented by five contourite channels (García 2002; Hernández-Molina et al. 2003), named the Cadiz, Guadalquivir, Huelva, Diego Cao and Gusano Channels, which are located on the southeast flank of the diapiric ridges. Also several minor marginal valleys, with irregular morphology and a NE–SW orientation are identified on the diapiric ridge's northwestern flank (García 2002; Hernández-Molina et al. 2003) (Figs. 1b and 2). The channels range from 10 to 350 m deep, are generally asymmetric with a steeper northern flank, extend from 10 km to over 100 km in length, and 1.5–10 km wide. They are broadly 'S'-shaped in planform, varying from a NW–SE direction along-slope to a NE–SW direction down-slope, due to the interference of the contour current with an irregular seafloor morphology (Fig. 1b).

Methodology

The present study was carried out using a broad database collected since 1989 and obtained during several cruises and projects, mainly supported by the Spanish Research

Table 1 Chronostratigraphy of the different orders of depositional sequences and tectonic unconformities for the Quaternary deposits of the buried mounded drifts and sheeted drifts of the central sector of the middle slope of the Gulf of Cadiz



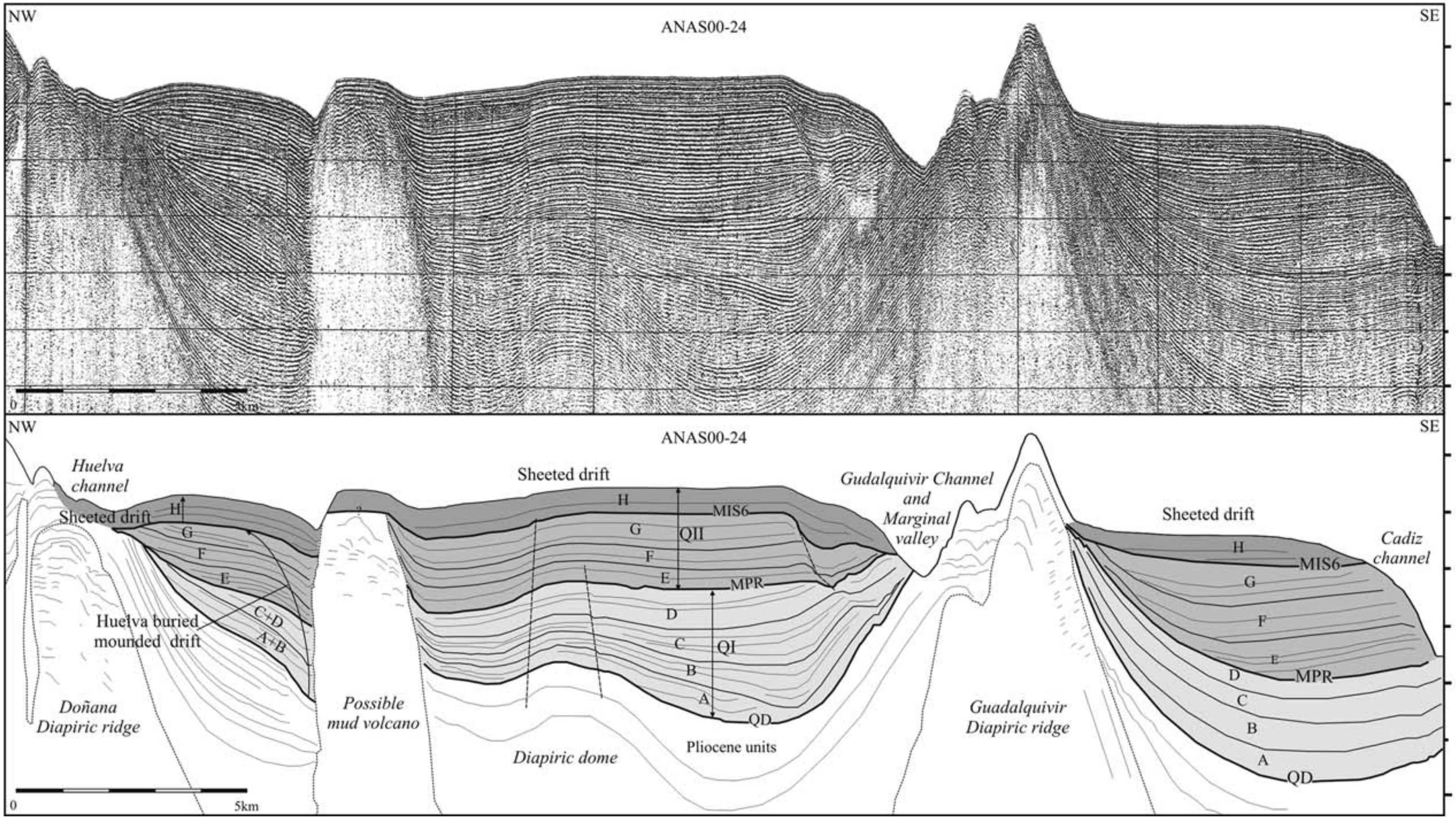


Fig. 2 Sparker seismic profile through part of the Channel and Ridge sector, located in the eastern area and crossing the main diapiric ridges, Doñana and Guadalquivir, affecting the contourite depositional system. Main tectonic and stratigraphy discontinuities are showed (see Fig. 1b for location)

Council. These data have enabled us to characterise the Pliocene and Quaternary regional seismic stratigraphy of the middle slope, to identify in detail the sedimentary environments and processes of each morphological sector of the present contourite depositional system, and to develop a better understanding of the margin evolution (Llave et al. 2001, 2006, 2007; Hernández-Molina et al. 2002, 2003; Llave 2003). In particular we focus on how this relates to the distribution of diapirs (Maestro et al. 2003; Fernández-Puga 2004). This database includes bathymetric, seismic, and core data:

(a) *Bathymetric data.* Regional bathymetric maps by Heezen and Johnson (1969) and Maldonado et al. (2004) were used in the first instance to identify the different morphological sectors and regional morphology. High resolution swath bathymetry from the middle slope was obtained using the Simrad EM12S-120 multibeam echo-sounder system.
(b) *The regional network of seismic data* analysed here includes: low-resolution multichannel seismic reflection profiles from oil companies, medium-resolution seismic profiles from Sparker and Airgun systems and ultra-high resolution seismic profiles using a Topographic Parametric Sounder (TOPAS).
(c) *Core and borehole data* studies carried out in the area were also correlated with seismic units and discontinuities of the present work to establish their chronology on the central area of the middle slope of the Gulf of Cadiz at different scales.

Results

Seismic stacking pattern of the main depositional features on the central sector: buried mounded and sheeted drift

A detail seismic stratigraphic analysis has been carried out in the central area of the middle slope. For simplicity we have followed the previously nomenclature described in the introduction and defined by Llave et al. (2001, 2007) and Hernández Molina et al. (2002) (Table 1).

In the central sector of the middle slope, the main Late Quaternary deposits are sheeted drifts, deformed by local tectonic activity and deeply eroded by channels. However, beneath these sheeted deposits, buried depositional features have been identified (Fig. 1b). They are composed of two main elongated, mounded, and separated contourite drifts (hereinafter referred to as mounded drifts): (1) the Guadalquivir Buried Mounded Drift is located south of the Guadalquivir Bank, at a water depth of 1,100 m. It is 15 km long and 6 km wide; (2) the Huelva Buried Mounded Drift is located on the southern margin of the present-day Huelva Channel, at a water depth of 650 m. It is 32 km long and 6 km wide. Both of these buried drifts are characterised by depositional sequences with a progradational sigmoidal-to-oblique landward configuration prograding over a palaeoslope (Figs. 2, 3 and 4). Buried mounded drifts are separated from the palaeoslope by a buried moat, designated as the Guadalquivir buried moat.

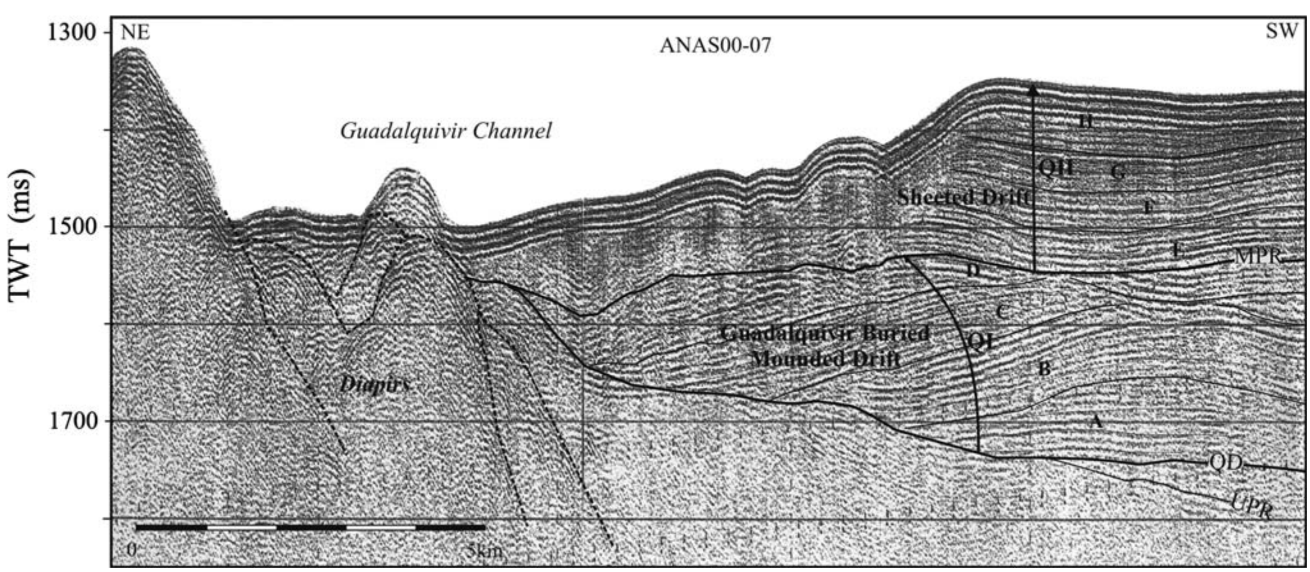
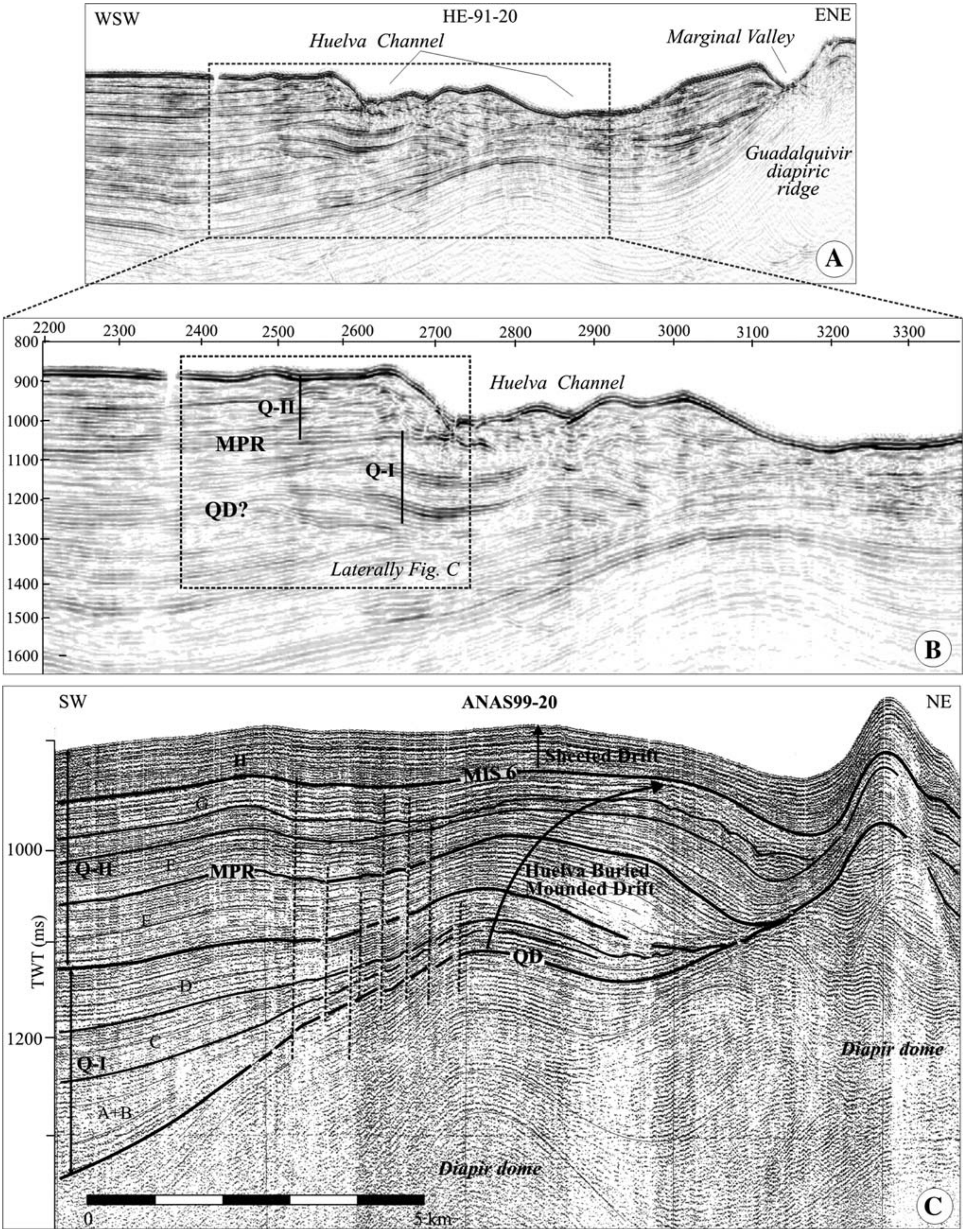


Fig. 3 Sparker seismic profile through part of the *Guadalquivir buried mounded drift* (GBD) of the western area of the central sector of the middle slope (see Fig. 1b for location). UPR, QD and MPR discontinuities and notice the mounded and progradational sequences A to D within the QI depositional sequence, and how they are buried by the entire QII depositional sequence


WSW
HE-91-20
ENE
Huelva Channel
Marginal Valley
Guadalquivir diapiric ridge
A
2200 2300 2400 2500 2600 2700 2800 2900 3000 3100 3200 3300
800 900 1000 1100 1200 1300 1400 1500 1600
Q-II
MPR
Q-I
QD?
Huelva Channel
Laterally Fig. C
B
SW
ANAS99-20
NE
Sheeted Drift
MIS 6
H
G
F
E
D
C
A+B
Q-II
MPR
Q-I
Huelva Buried Mounded Drift
QD
Diapir dome
Diapir dome
TWT (ms)
1000
1200
0
5 km
C

◀**Fig. 4** (**a** and **b**) Uninterpreted Multichannel seismic reflection profile across the middle slope, where UPR, QD and MPR discontinuities and QI and QII depositional sequences are showed (provided by REPSOL-YPF Oil Company for the present work). (**c**) High resolution sparker seismic profile through part of the *Huelva buried mounded drift* (HBD) of the northern and eastern area of the central sector of the middle slope (see Fig. 1b for location). Main tectonic and stratigraphy discontinuities are showed

Two main depositional sequences are identified in the Quaternary sedimentary record of the central sector of the middle slope: QI and QII (Figs. 2–5; Table 1). These sequences are separated by a marked continuous reflector of strong amplitude, and highly reflective and erosive surface named the MPR discontinuity. The base of these two depositional sequences is constituted by a high amplitude reflection, which constitutes an erosive surface named the Quaternary Discontinuity (QD).

Sequence QI is made up of the superposition of four minor depositional units (Figs. 2–5): A, B, C and D (from oldest to youngest). They have a generally lenticular geometry and are bounded by minor erosive and reflective surfaces, considered to be the main discontinuities, and named from oldest to youngest: the Quaternary Discontinuity (QD), MIS 46, MIS 40, MIS 32 and MPR (Table 1). Sequence QII is bounded at the base by the MPR discontinuity and at the top by the present-day sea floor (Figs. 2 and 3). The sequence comprises four minor depositional units (Figs. 2–5): E, F, G and H, bounded by minor reflective and erosive discontinuities. These discontinuities are from oldest to youngest: MPR, MIS 16, MIS 12, MIS 6 and the sea floor (Table 1). A similar seismic facies trend is observed in each depositional sequences and units, including: (a) a transparent zone at the base; (b) smooth, parallel reflectors of moderate-to-high amplitude in the upper part; and (c) an erosive continuous surface of high amplitude at the top (Figs. 3 and 4c).

The described stratigraphic stacking pattern of the depositional sequences is different in both the Guadalquivir and Huelva Drifts, showing a differential time interval for their activity, especially during the deposition of Sequence QII:

(a) *The Guadalquivir buried mounded drift* is approximately 300 ms (two-way travel time (TWT)) thick and exhibits an upslope, northeastwardly prograding stacking pattern (Sequence QI). This depositional sequence has been buried by an aggrading stratified depositional sequence (Sequence QII) approximately 175 ms (TWT) thick, which is now partially eroded as a consequence of the present-day Guadalquivir Channel (Fig. 3). The MPR discontinuity, therefore, constitutes an important erosive truncated surface, which separates the prominent prograding body (Sequence QI), from a more aggradational one (Sequence QII) (Fig. 3).

(b) *The Huelva buried mounded drift* represents a buried, mounded drift in the Quaternary record identified by multichannel seismic reflection profiles (Fig. 4a and b). This mounded drift was prograding northward during deposition of both Sequences QI and QII, but progradation within Sequence QII can be identified more accurately with medium-resolution seismic profiles from Sparker (Fig. 4c). In the Sparker seismic lines the mounded drift is also characterised by a prominent northeastwardly progradation of internal reflectors, whereas the main axis of the body trends northwestwards. It is more than 400 ms (TWT) thick and comprises several depositional units (named from A to H up-section). This drift is partially preserved by the most recent H depositional unit, which is 50–70 ms (TWT) thick and shows an aggradational stacking pattern, characterised by stratified, subparallel, high- and low-amplitude reflections. Consequently, the change in depositional style of the mounded drift is related to the base of Unit H, and is observed over most of the central sector associated with the Huelva buried mounded drift. However, locally in the central part between the Guadalquivir Diapiric Ridge and the Guadalquivir Bank, this unit shows a progradational configuration preserving the mounded morphology as the effects of the previous physiography (Fig. 5).

The basinward prolongation of both buried, mounded drifts (Guadalquivir and Huelva Drifts) is a deformed sheeted drift, as inferred from an aggrading stacking pattern, with alternating transparent and reflective units affected by anticline and syncline structures, The deformed sheeted drift is mainly characterised by stratified and continuous reflectors, although locally it is possible to observe a more chaotic, undulating and discontinuous

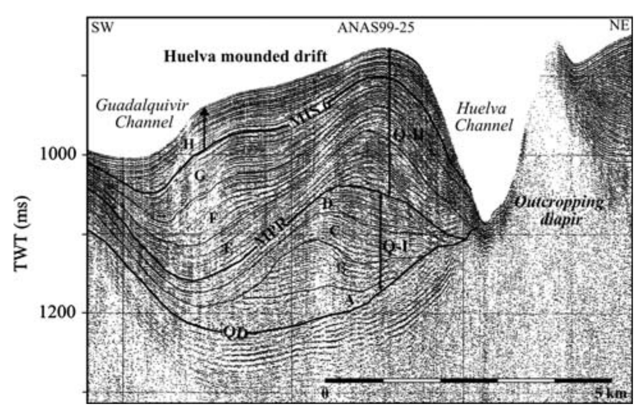


Fig. 5 High resolution sparker seismic profile through part of the *Huelva buried mounded drift* (HBD) of the central sector of the middle slope (see Fig. 1b for location). Main tectonic and stratigraphy discontinuities are showed

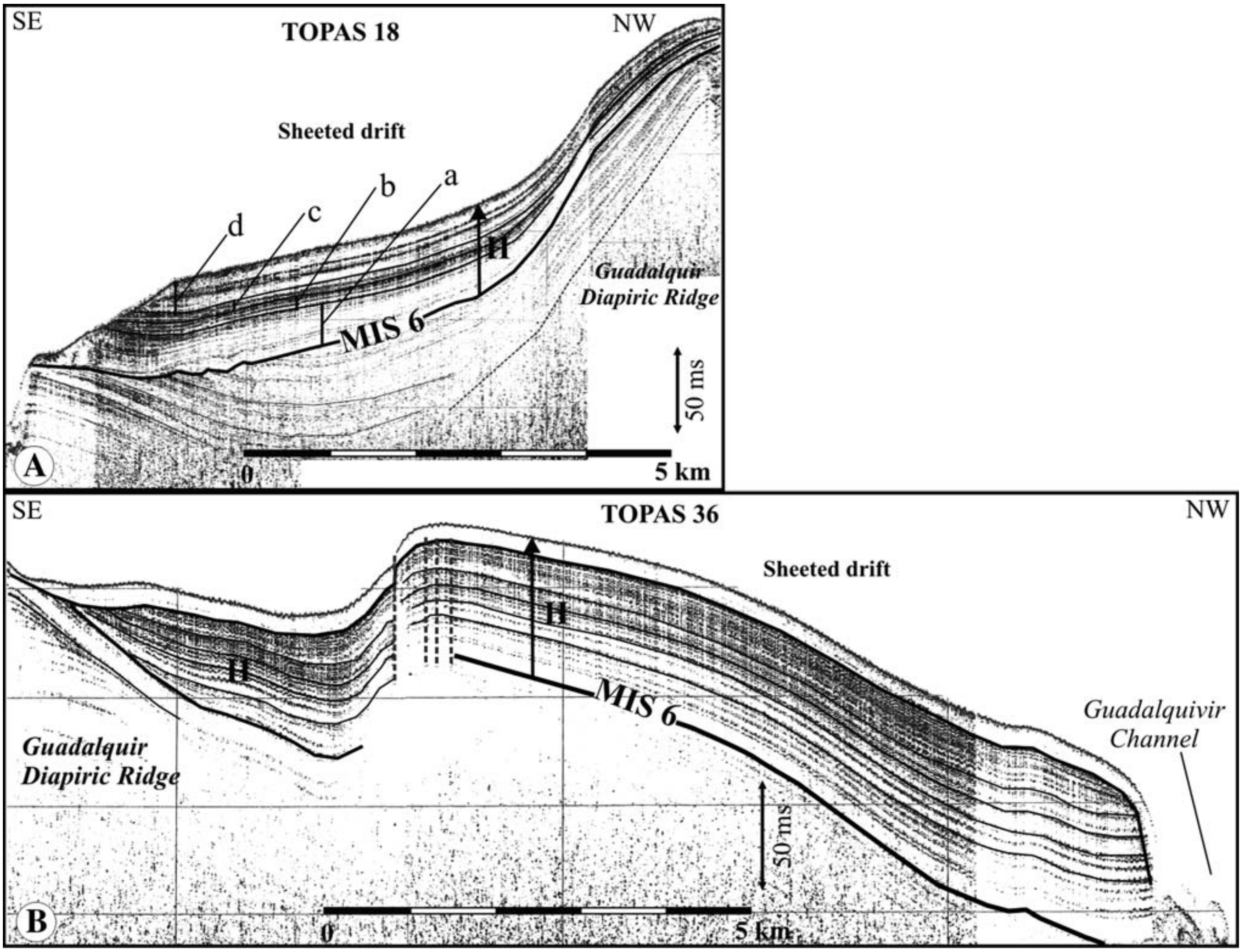


Fig. 6 (**a**) Ultra high resolution seismic profile showing the minor seismic units within the H sequence of the eastern area of the central sector of the middle slope (modified from Llave et al. 2007); (**b**) Ultra high resolution seismic of the western area of the central sector of the middle slope (see Fig. 1b for location). Unconformity U6 and folding and faulting of H depositional sequence can be notice on both lines

reflector pattern. In some parts of this central sector, the most recent deposits are also eroded by separate branches of the Guadalquivir Channel (Fig. 1b). The deformation of these deposits is most important in the eastern part of the sheeted system, due to the existence of numerous buried diapirs and normal faults (Figs. 1b, 2, 4 and 6a). In the western sector, the sheeted drift is less deformed, having a general aggrading stacking pattern, but locally deformation forms gentle waves with low amplitude and low frequency (Figs. 1b and 6b).

Depositional Unit H is characterised by an average thickness of 50 ms (TWT) and the presence of several elongate depocenters, trending either NE–SW or NW–SE, which have a maximum thickness of approximately 100 ms (TWT) (Fig. 7). A decrease in thickness is observed westward and in those areas where channels and ridges are present.

Within depositional Unit H, in the southeastern part of the channels and ridges sector, four minor subunits bounded by erosive surfaces are observed (Fig. 6). As with the major sequences, these also display an alternation of transparent and reflective seismic facies, together with some minor erosive surfaces. They have been designated, from oldest to youngest, as subunits *a*, *b*, *c*, and *d* (see for further details Llave et al. 2004a, 2007). In this area, the base of Unit H is a clear erosive boundary truncating the underlying sequence (Fig. 6). The eastern part of the area is characterised by younger units, with an aggradational pattern truncating the tilted underlying units (Fig. 6a). The western zone is characterised by a transparent unit, which appears to have buried a recent erosive truncation. The whole contourite sequence in this zone is also affected by a major SE–NW trending normal fault (Fig. 6b).

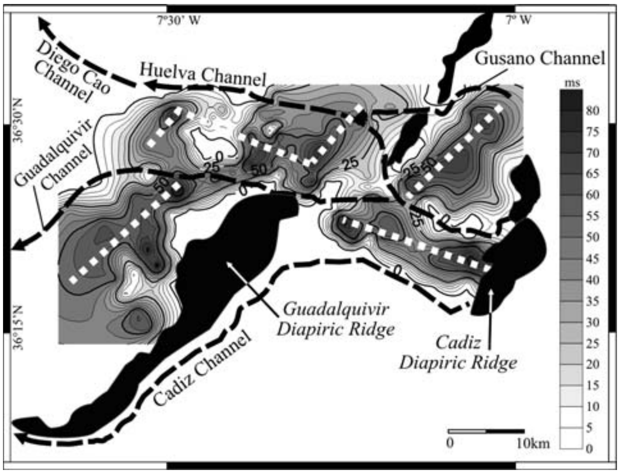


Fig. 7 Isopach map in milliseconds of seismic unit H above the *Huelva buried mounded drift* in the channels and ridges sector of the middle slope of the Gulf of Cadiz. The distribution of the main depocenters is showed (white dot line), and the present situation of the main contourite channels (black dash lines) and diapiric ridges (solid black), with a NNE–SSW direction is represented

Deformational processes in the central sector affecting the buried drifts

The Guadalquivir and Huelva buried drifts are quite tilted and folded as a consequence of salt diapirs and mud volcanoes that occasionally emerge, rise above the seafloor, and extrude because the density of salt and mud is lower than that of adjacent, compacted overlying sediments (Fig. 2). The main diapiric structures are called the Doñana, Guadalquivir and Cadiz Ridges. Moreover some isolated diapirs, outcropping or not, are also affecting these buried mounded drifts (Figs. 2 and 4b). It can be observed that the diapiric ridges are intrusive bodies under Sequence QI. Above horizon QD, we observed a slow reactivation with tilting and subsidence of the Quaternary depositional units, especially from Units A to G (Fig. 2). The upward diapiric motion forms small-scale normal faults and folds that can be observed in the seismic reflection profiles. Generally, these faults are located in the crest of diapirs and form symmetric grabens that also affect the depositional Units A to G (Figs. 2 and 4c).

The depositional units show subparallel seismic reflectors with onlapping structures near the diapiric features. Deformation of the buried drifts is inversely related to their distance from the main diapiric bodies, as shown most clearly in the deformation, which causes the oldest drift units to outcrop adjacent to the larger diapiric structures (Fig. 2). Sediments deposited during diapiric growth are characterised by thinning toward the axis of uplift and only minor thickening into relatively distant peripheral sinks. The progressive development of diapiric ridges has formed a synclinal structure as a result of tectonically induced subsidence between the ridges (Fig. 2).

Unconformities and deformational features observed in the Quaternary sedimentary record can be used to determine the relative timing of tectonic processes. In general, it is clear that the geometry and sedimentary evolution of the contourite depositional system has been controlled by the reactivation and the development of diapirism. Between the Guadalquivir Bank and the Guadalquivir Diapiric Ridge (Figs. 2–5), the main unconformities recognised in the sedimentary record (i.e., MPR and MIS6), coincide with the most important uplift stages of the diapiric bodies (Event 1 and Event 2) (Table 1). These unconformities are only influenced by diapirism in this central sector of the middle slope, leading to the end of the drift development and hence burial of the mounded contourite deposits (Table 1).

In the eastern zone, deformation is mainly marked by the development and outcropping of the Guadalquivir and Doñana Diapiric Ridges, which resulted in folding and faulting of Sequences QI and QII. These deformations affect the seafloor, and produce an elongated, wave-shaped morphology with a NE–SW orientation (Figs. 4c and 5).

Discussion

Climatic and diapiric control on the growth and burial of mounded drifts

The chronostratigraphic framework indicates that the main discontinuities are related to an enhancement of Mediterranean Outflow Water leading to widespread regional erosion during the cold climate, lowstand periods. The main contourite deposition took place during the transition from warm to cold periods, i.e. under regressive to lowstand conditions.

The contourite depositional system in the Gulf of Cadiz is a direct consequence of the interaction of Mediterranean Outflow Water with the seafloor along the middle slope. The general stacking pattern during the Quaternary is influenced by climatic and sealevel changes (Hernández-Molina et al. 2003, 2006b; Llave et al. 2007; Llave 2003). In this sense the change observed in the sedimentary record before and after the MPR discontinuity, which divides the oblique prograding Sequence QI from the more sigmoidal-oblique prograding and thicker Sequence QII, appears to be correlated regionally with the important climatic change known as the Mid-Pleistocene Revolution (Table 1). In the same way, the minor depositional units, termed A, B, C, D (for QI) and E, F, G, H (for QII), constitute asymmetric 4th-order sequences of around 200 ky

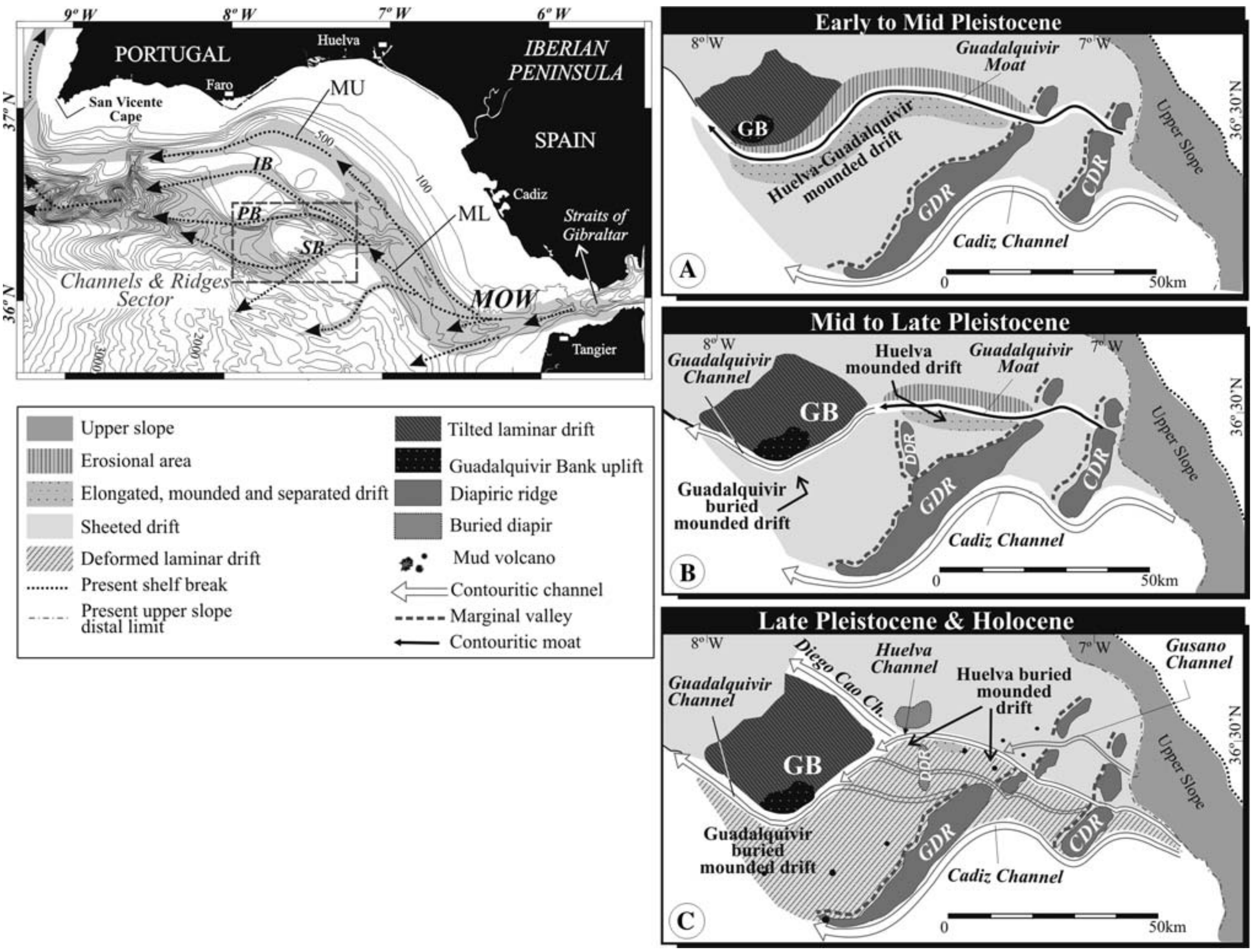


Fig. 8 Interpretative sketch of the Quaternary evolution of the buried mounded drift deposits in the *Channels and Ridges Sector* of the middle slope of the Gulf of Cadiz. Three different stages have been identified: (**a**) *active Guadalquivir and Huelva drift growth stage* (Early to Mid Pleistocene); (**b**) *late-stage drift growth* (Middle-Late Pleistocene) and (**c**) *complete drift burial* (Late Pleistocene and Holocene) when the present morphologic configuration of this sector was generated by new oceanographic conditions of the Mediterranean Lower Water (ML). See text for further details. *Legend* = GB = *Guadalquivir Bank*, DDR = *Doñana Diapiric Ridge*, GDR = *Guadalquivir Diapiric Ridge*, CDR = *Cadiz Diapiric Ridge*

duration, separated by minor erosive discontinuities, which are correlated with falls in sea level produced by the most prominent Quaternary events (Table 1). The most recent depositional sequence, Unit H, is composed of four subunits bounded by erosive discontinuities, that have been influenced by cold climatic periods as Heinrich events, Last Glacial Maximum and Younger Dryas (for details see Llave et al. 2006).

Changes in the depositional style observed in the stacking pattern and distribution of both the Huelva and Guadalquivir buried mounded drifts (Fig. 8) demonstrates that diapiric uplift has also had a long-term influence on Quaternary contourite sedimentation. Two major diapiric events have been identified:

(a) *Event 1*. This first event produced a change in the depositional pattern of the Guadalquivir Drift from a mounded depositional style to a sheeted one, and is coeval with the MPR regional stratigraphic discontinuity. This change correlates with the uplift of the Guadalquivir and Doñana Diapiric Ridges, which produced major changes in the pathway of the Guadalquivir Channel (Fig. 8 and Table 1).

(b) *Event 2*. The second recent tectonic event is coeval with the regional MIS 6 discontinuity (Fig. 4 and Table 1), involving a reactivation of diapiric ridge structures, normal faulting and erosive channels (Llave 2003; Fernández-Puga 2004). This clearly marked a major change in the general conditions of the depositional system and especially in the depositional style of the buried Huelva Drift, which changed from a mounded depositional Unit G to a sheeted depositional Unit H, in those zones closer to the Guadalquivir Diapiric Ridge.

The diapiric reactivation during these two events that are contemporary with the MPR and MIS 6 stratigraphic discontinuities (coeval with major sea level falls and glacial climatic periods during the Quaternary) can be explained in two possible ways: (A) Tectonic Event 1 could be associated with intensification of the compressive regime (Rodero 1999; Rodero et al. 1999), and Tectonic Event 2 could be related to the reactivation of the diapiric ridges and with isolated diapiric intrusion described by Pérez-Fernández (1997) and Rodero (1999). (B) The diapiric reactivation could be related to glacial/interglacial sea level fluctuations (Bouma 1981; Flood et al. 1995; Felser et al. 1998). During periods of lowstand (glacial periods) material is eroded from the continental shelf and deposited on the margin and in the deep sea. The rapid sea level drop at the beginning of a glacial lowstand would have given a strong sedimentation pulse in the middle slope. The deposition of excess sediment may have caused a loading effect leading to a renewal of upward diapiric motion or to an increase in its rate. This accelerated upward motion of the diapirs may become effective at the time when lowering of sea level ceases. Thus, indirectly, interglacial/glacial sea level changes may help create the observed major unconformities.

The diapiric activity has been related to the recent origin of the channels and ridges sector (Hernández-Molina et al. 2003, 2006b; Llave 2003), the genesis of the Diego Cao Channel (Llave et al. 2001) and recent over-excavation of the Cadiz Channel described by García (2002). We therefore propose that diapiric episodes coeval with the MPR and MIS 6 regional discontinuities have played a major role in controlling long-term evolution of the contourite depositional system on a broad scale. At the short-term scale, environmental changes (climate and sea level) have further influenced development of the individual depositional sequences, units and subunits.

Mounded drifts evolution during the Quaternary: changes in the Mediterranean Outflow Water

Three main stages in the Quaternary evolution of the contourite drifts in the central sector of the middle slope have been identified (Fig. 8).

Initial-stage mounded drift growth (Early to Mid-Pleistocene)

This first stage is represented by Sequence QI, during whose deposition the extensive Huelva and Guadalquivir buried mounded drifts developed (Fig. 8a). These drifts are located between Guadalquivir Diapiric Ridge on the east and Guadalquivir Bank on the west, and developed on the left flank of the Guadalquivir buried moat. These depositional features were generated by the interaction of Mediterranean Lower Core Water with an irregular seafloor, where turbulent and intensified flow conditions caused the focusing of Mediterranean Outflow Core Water. As Mediterranean Lower Core Water became channelled, it affected the development of the sinuous Guadalquivir Moat. Deflection of the flow by Coriolis force led to progressive erosion of the right flank of the moat, coupled with deposition of the Huelva and Guadalquivir elongated, mounded and separated drifts on the left flank, where the current was slower. During this stage, the Guadalquivir Diapiric Ridge represented a more continuous structure than at present, allowing only one main branch of the Mediterranean Lower Core Water to pass through the ridge toward the west.

The basinward prolongation of the Huelva and Guadalquivir buried mounded drifts was marked by an extensive sheeted drift, occupying the main central sector (Fig. 8a). These contourites were deposited synchronous with diapiric ridge activity and were then eroded by the Cadiz Channel in the south and by the marginal valleys generated on the northern part of the diapiric ridges.

Late-stage mounded drift growth (Middle-Late Pleistocene)

During this second stage, when most of Sequence QII was deposited, the Huelva mounded drift spread out from the Guadalquivir Diapiric Ridge in the east and towards the Doñana Diapiric Ridge in the west (Fig. 8b) (Sequences E, F and G). The basinward prolongation of the Huelva buried, mounded drift was marked by a widespread sheeted drift subsequently deformed by diapirism and eroded by the Cadiz Channel to the south, as well as by the marginal valleys on the diapiric ridge's northwestern flanks. On the other hand, the Guadalquivir mounded drift became inactive in the westernmost area, and in its place an extensive sheeted drift was developed, burying the mounded drift. This change in the depositional style, correlating with Tectonic Event 1, occurred during the Mid-Pleistocene, which led to reactivation of the main diapiric ridges, and outcropping at the seafloor of parts of the Doñana Diapiric Ridge. Consequently, new oceanographic conditions related to flow of Mediterranean Lower Core Water were established. The Guadalquivir buried moat was developed in the zone bordered by the Guadalquivir and Doñana Diapiric Ridges. Its right flank was progressively eroded, while deposition of the Huelva mounded drift took place on the left flank. During this stage, we assume that the

Guadalquivir Diapiric Ridge remained a more continuous structure, and only one main branch of the Mediterranean Lower Core Water could have passed through the ridge toward the west. Meanwhile, the Guadalquivir Channel became active between the Doñana Diapiric Ridge and the Guadalquivir Bank.

Complete mounded drift burial stage (Late Pleistocene to Holocene)

In this last evolutionary stage no mounded drift was developed in the central sector of the middle slope. This stage was marked by an important change in physiography of the slope, Event 2, which took place at the beginning of the Late Pleistocene ($\sim$135 ka) and coeval with the MIS 6 regional discontinuity. This second event is associated with the reactivation of the diapiric ridges and with isolated diapiric intrusions, which produced a widespread and complex system of contourite channels and sheeted drifts, nearly burying the Huelva mounded drift during deposition of depositional Unit H. As a result of Event 2, the Guadalquivir Diapiric Ridge no longer remained as a fully continuous structure. Several small passageways were generated through the ridge, which resulted in the formation of the three main branches of the Mediterranean Lower Core Water observed today (Southern, Principal and Intermediate Branches). The present morphological configuration of the channels and ridges sector was generated by these new oceanographic conditions (Fig. 8c). Consequently, in this last stage the central sector of the middle slope was dominated by erosive processes, most prominently by the five sinuous channels (Cadiz, Guadalquivir, Huelva, Diego Cao and Gusano Channels), as well as by the diapiric ridge features (Figs. 1b and 8c). The sheeted drifts of depositional Unit H were also deposited at this time, coincident with continued channel erosion and diapiric deformation.

Conclusions

Our analysis and interpretation of the Quaternary sedimentary record of the central sector of the middle slope of the Gulf of Cadiz indicates that contourite sedimentation has been influenced by both climatic and tectonic changes, both controlling the Mediterranean Outflow Water pathways distribution and hydrographic conditions at short and long time scales.

Two buried mounded contourite drifts were deposited during the Quaternary between the Guadalquivir Diapiric Ridge to the east and the Guadalquivir Bank to the west, but each has shown independent evolution in depositional style during this period. At the beginning of the Quaternary, both buried contourite deposits were composed of elongated, mounded and separated drifts bounded by the buried Guadalquivir Moat. After the Mid Pleistocene Revolution, coinciding with a tectonic event which produced the uplift of the Guadalquivir and Doñana Diapiric Ridges, the mounded pattern only occurred in the eastern part of the system (Huelva mounded drift) and a sheeted drift was developed in the western part. This tectonic activity produced changes in the Mediterranean Lower Core Water, and hence a change from major erosion along the Guadalquivir Moat in the east, to more dominant erosion of the Guadalquivir Contourite Channel in the west. Within the Huelva buried mounded drift, a change in the depositional style is related to the base of depositional Unit H (beginning of the Late Pleistocene). During this time a tectonic regional event took place that produced the redistribution of the diapiric ridges, leading to the opening of multiple pathways for the Mediterranean Outflow Water, as is evident in the complex configuration of the study area at the present day, where erosion processes dominate and a deformed sheeted drift is developed.

The two regional Quaternary tectonic events that generated discontinuities MPR and MIS 6 are associated with uplift of the diapiric ridge structures and associated fault activity, which have together controlled changes in the regional circulation of Mediterranean Lower Core Water. These changes led to inactivity and burial of the mounded drift system in two different phases, as well as to the recent origin of the channels and ridges sector. The sedimentary record and evolution of the central sector of the middle slope allows us to decode important palaeoceanographic events related to recent tectonic and fluctuations in Mediterranean Outflow Water. A progressive increase in overall intensity of Mediterranean Outflow Water velocity can be identified culminating in the dominance of erosive processes over much of the region during accumulation of the younger depositional unit (H).

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