

Preface

Virtual special issue on IODP Expedition 339: The Mediterranean outflow



1. The virtual special issue (vsi)

IODP Expedition 339 had two inter-related objectives to recover continuous sedimentary sequences for: (i) studying the Contourite Depositional System (CDS) formed by the MOW; and (ii) reconstructing North Atlantic climate variability on orbital and suborbital time scales. This Elsevier Virtual Special Issue (VSI) “*Mediterranean Outflow*” is comprised of two volumes that are roughly divided along these lines with *Marine Geology* devoted to (i) and *Global and Planetary Change* to (ii), although some papers overlap the two themes. The *Marine Geology* volume contains 9 contributions addressing specific aspects of IODP Expedition 339 related to contourite deposits including sedimentology, seismic interpretation, stratigraphy, physical properties, downhole logging and ichnofacies. The *Global and Planetary Change* volume consists of 18 papers highlighting paleoclimatic results from sites drilled on the SW Iberian Margin and in the Gulf of Cadiz. The two volumes provide a sample of emerging results of Expedition 339 and foretell of the promising research yet to come.

2. Drilling IODP Expedition 339

Integrated Ocean Drilling Program (IODP) Expedition 339 (Fig. 1) represented the merger of two drilling proposal: IODP Proposal 644-

Full2 and ancillary proposal letter (APL)-763 (see Hernández-Molina et al., 2013; Hodell et al., 2013; Stow et al., 2013a). The expedition was primarily paleoceanographic in nature, focusing mainly on the broader significance of Mediterranean Outflow Water (MOW) on North Atlantic Ocean circulation and climate (Expedition 339 Scientists, 2012). This expedition offered a rare opportunity to understand the global link between paleoceanographic, climatic, and sea level changes from Latest Miocene (Messinian) to Recent and to address the importance of ocean gateways in regional and global ocean circulation and climate. The Gulf of Cadiz was selected as a key location for the investigation of MOW and for understanding the effects of tectonic activity on evolution of the Gibraltar Gateway and on margin sedimentation. The SW Iberian Margin and Gulf of Cadiz were targeted for their rapidly accumulating sediments that contain a high-fidelity record of Quaternary millennial-scale climate variability. In particular, Site U1385 (the “Shackleton site”) was identified as an important type section for marine-ice-terrestrial core correlations and the study of orbital- and millennial-scale climate variability.

The extensive CDS within the Gulf of Cádiz, and extending around the West Iberian margin, has developed over the past 5.3 Ma as a direct consequence of MOW (e.g., Madelain, 1970; Gonthier et al., 1984; Faugères et al., 1985; Nelson et al., 1993, 1999; Llave et al., 2001, 2006, 2007a, 2007b, 2011; Stow et al., 2002, 2013b; Habgood et al., 2003;

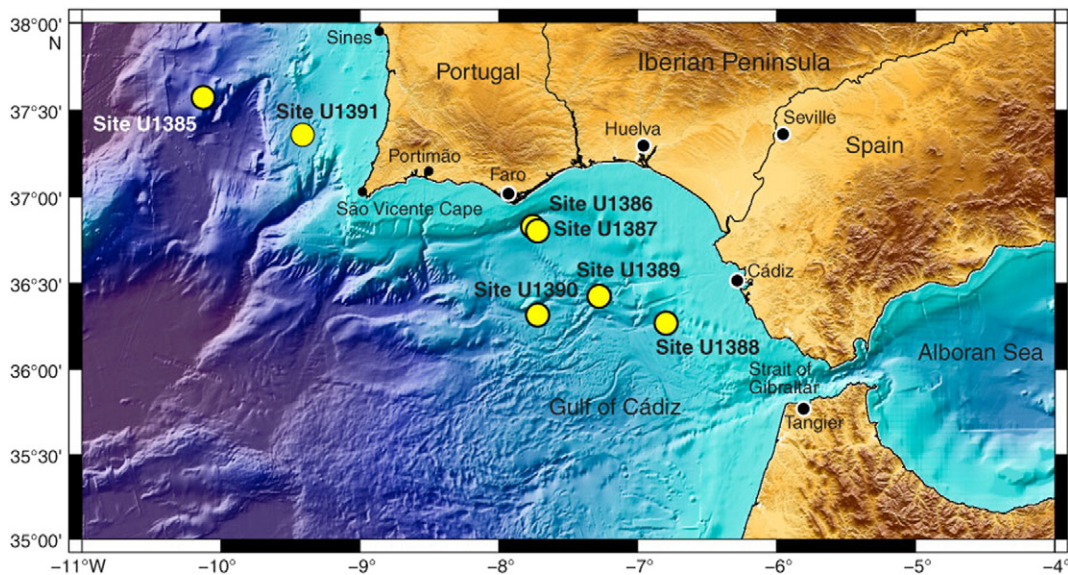


Fig. 1. Expedition 339 sites in the Gulf of Cádiz and West Iberian margin, shown as yellow solid circles.

Hernández-Molina et al., 2003, 2006, 2011, 2014a, 2016; Mulder et al., 2003, 2006; Hanquiez et al., 2007; Marchès et al., 2007; Roque et al., 2012; Brackenridge et al., 2013). The high accumulation rates and expanded sedimentary records of these drift deposits permit detailed examination of past environmental change (Llave et al., 2006; Voelker et al., 2006). The CDS deposits preserve a high-fidelity signal of MOW flow through the Strait of Gibraltar gateway and a clear record of its influence on the oceanography and climate of the North Atlantic Ocean, including North Atlantic Deep Water formation (Hernández-Molina et al., 2014b). Despite the fact that the Gibraltar Gateway clearly has major implications for global climate and oceanography, the region had not been drilled previously for scientific purposes.

The SW Iberian Margin and Gulf of Cadiz are well known areas of rapidly accumulating sediment that contain a high-fidelity record of millennial-scale climate variability for the late Pleistocene. The surface water in the region is particularly sensitive to past migrations of the Polar Front and sea ice expansion in the North Atlantic, yet it is far enough south and east to avoid the problems associated with oligotrophic meltwater and 'proxy saturation'. Intermediate depth sites on the margin document past variations in the position and intensity of MOW, whereas deeper sites along the lower slope are sensitive to the mixing ratio of northern- and Antarctic-sourced deep waters. Moreover, the proximity to land and the relatively narrow continental shelf enables delivery of terrestrial material, including pollen, to the deep-sea

environment, thereby permitting direct correlation to European terrestrial sequences. Previous work on piston cores from the region have demonstrated the great potential of the sediment record for correlating marine climate records to the polar ice cores and European terrestrial sequences.

Expedition 339 drilled five sites in the Gulf of Cádiz (U1386–U1390) and two sites off the west Iberian margin (U1385 and U1391) from 17th November 2011 to 17th January 2012 (iodp.tamu.edu/scienceops/expeditions/mediterranean_outflow.html, Figs. 1 and 2). Six of the sites, U1386–U1391, were specifically selected in order to study the contourite depositional system (CDS) generated by MOW along the middle slope, and the "Shackleton site" (U1385) was drilled on the lower slope off Portugal for paleoclimate studies (Fig. 2). All three standard coring systems available onboard JOIDES Resoluton were employed during Expedition 339, including the advanced piston corer (APC), the extended core barrel (XCB), and the rotary core barrel (RCB) (Stow et al., 2013a). In total, nearly 5.5 km of core were recovered, with an average core recovery of 86.4% (Figs. 2 and 3).

3. Introduction to marine geology volume

This Marine Geology volume, contains 9 selected contributions that mainly address important contourite-related issues from the IODP Expedition: stratigraphy, seismic interpretation and sites correlation;

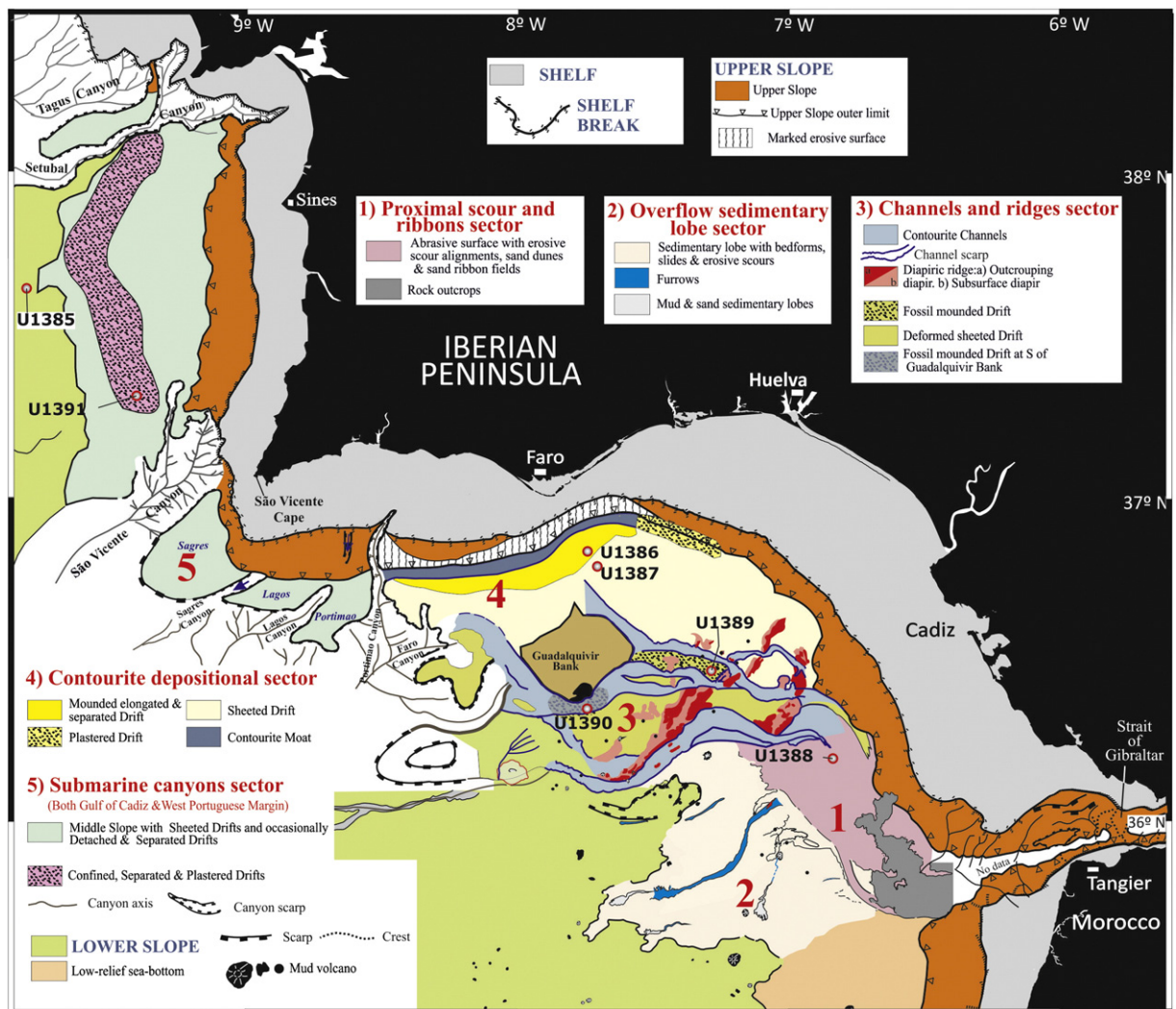


Fig. 2. Regional map of the contourite depositional system along the middle slope of the Gulf of Cádiz and West Iberian margin with Expedition 339 site locations. Morphosedimentary sectors (1–5) based on Hernández-Molina et al. (2003, 2006, 2013, 2014a).

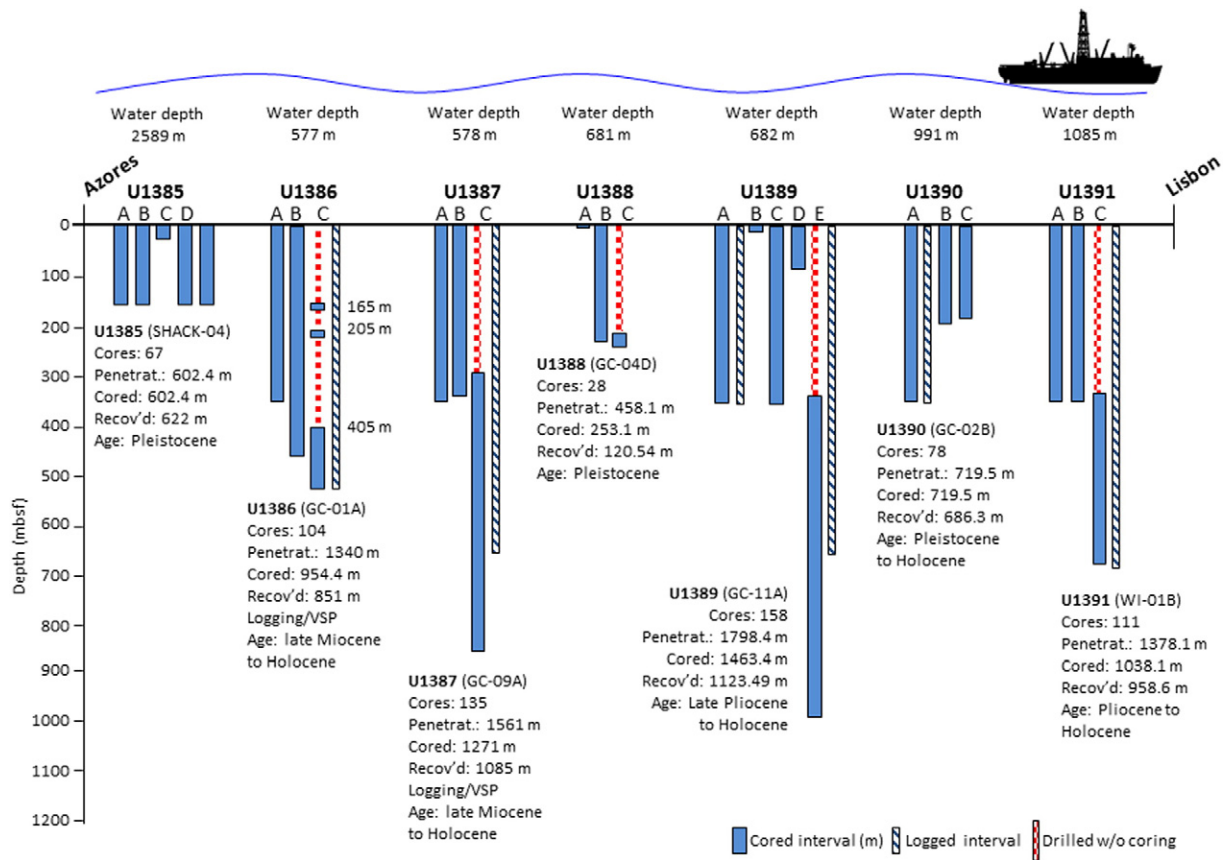


Fig. 3. Expedition 339 sites. 19 holes (681 cores) were drilled in 46.1 days with a penetration of 7857.4 m, cored 6301.6 m and recovered 5446.7 m (86.4%).

sedimentology / lithostratigraphy, physical properties, downhole logging, and ichnofacies.

Hernández-Molina et al. (2016) integrate results from IODP Exp. 339 and borehole data from industry sources with other geophysical databases and onshore outcrop analysis. They propose a new stratigraphic framework and refine the understanding of the Southwestern Iberian Margin (SIM) sedimentary evolution. They interpret major changes in depositional style, sedimentation rates and SIM margin evolution from the Pliocene through the Quaternary within the Neogene (Cadiz, Sanlucar, Doñana, Algarve and Alentejo) basins, and evaluate the broader tectonic, paleoceanographic and climatic implications of these events. These authors propose three major stages in the evolution of the Contourite Depositional System, demonstrating that sedimentation is controlled by a combination of tectonics, sediment supply, sea-level and climate. Their research identifies time scales of tectonic controls on deep-marine sedimentation, specifically over periods of 2.5 - >0.4 My. Shorter-term climatic (orbital) mechanisms control sedimentation at time scales of ≤ 0.4 My.

Lofi et al. (2016) analyze core and downhole Gamma Ray (GR) data from 6 sites drilled during Exp. 339 in order to investigate how the GR signal responds to changes in lithology and associated paleoenvironments within the Cadiz, Sanlucar, Doñana, Algarve and Alentejo basins. They correlate and track the Pleistocene deposits and contourite beds at the regional scale over the last 1.4 My in order to reconstruct their spatial variability and test the existing scenario of enhanced MOW during cold climatic conditions. The GR data primarily tracks the clay content in the sediment and is an expression of sediment supply and bottom current processes. Both appear astronomically controlled as shown by spectral analysis performed on the GR data. Some GR horizons are interpreted as isochronous horizons. This work provides the first regional scale chronostratigraphic framework for the last 1.4 Ma.

Ducassou et al. (2016) study the gravitational deposits (debrites) presented in the sedimentary record from the early Pliocene (4.5 to 3.5 Ma) and early Pleistocene (1.66–1.25 Ma) at Site U1386 on the Faro Drift in the Deep-Algarve basin. This study examines sedimentologic characteristics, micropaleontological compositions and source(s) of debrites and determines their ages. They indicate that these debrites were triggered on the continental shelf and traveled less than 100 km, eroding the seafloor, and interacting with the MOW, especially during the early Pleistocene. These authors propose that tectonic and diapiric activities were significant on the Algarve margin during the studied periods and could have been triggers of these debris flows.

Alonso et al. (2016) characterize the Pleistocene lithofacies based on sedimentological and mineralogical properties from Sites U1386 and U1387 on the Faro Drift in the Algarve basin, and identify the main diagnostic features for distinguishing contourite and gravity-flow deposits. In addition, they define a model of facies distribution for the depositional architecture of the Pleistocene Faro Drift deposits. They have identified three lithofacies, A (Contourites deposits) B (Turbidites) and C (Debrites), using a combination of sedimentological and mineralogical analyses. These authors propose that the main criteria used to distinguish between these deposits are the vertical trend of the grain-size and the sedimentary structures, the modal frequency distribution, and the sediment composition and provenance that reflect long- and short-distance transport modes. The spatial and temporal distributions of these lithofacies reflect the different (palaeo) environments of the Faro Drift.

Takashimizu et al. (2016) evaluate the genesis of Younger Sand layers (YSLs) found at Sites U1386, U1387, U1389 and U1390 within the Sanlucar, Doñana and Algarve basins, using grain size analysis, ichnofacies and accelerator mass spectrometry (AMS) radiocarbon dating. These layers have been identified in drill cores at three distinct

times: 1) the Bølling-Allerød; 2) the Younger Dryas, and; 3) the beginning of the Boreal period. They present a detailed sedimentary and stratigraphic analysis that includes a description of bottom current related sandy deposits and propose these criteria can be used to identify similar deposits in ancient contourites. These authors discuss potential source areas for the sandy sediments and suggest the possibility of a tsunami-related origin for the YSLs that were later reworked by bottom currents.

Nishida (2016) investigate the microstructure of muddy contourites from Sites U1386 and U1387 in the Algarve basin, focusing on potential diagnostic characteristics for discriminating them from hemipelagites and other deep-sea deposits. The authors analyzed the magnetic fabric and grain-size distribution and indicate that they are useful criteria for discriminating muddy contourites from hemipelagites. On the basis of these features, the plate-like silt particles, which are parallel or sub-parallel to the bedding plane in the muddy contourites, are interpreted to reflect rapid deposition from a low-concentration suspension of fine-grained particles in a weak bottom current.

Dorador and Rodríguez-Tovar (2016a, 2016b) present two papers in this volume. In the first, they characterize the ichnofabric of Site U1385 during the Pleistocene. They execute a comparative analysis between ichnofabrics, with special attention to the amount of bioturbation, grouping, ichnofabric succession/transitions and vertical distribution, to shed light on paleoenvironmental implications. They present seven ichnofabrics with significant differences in terms of ichnofabric features, environmental parameters, as well as in their stratigraphic distribution. Types of ichnofabrics and the Bioturbation Index show significant short-term changes probably correlated to millennial-scale climatic perturbations, or long-term cyclic patterns related to orbital climate variability. In their second contribution they conduct a color analysis on selected cores from Sites U1385 and U1389. This analysis is based on a recently developed high-resolution digital image treatment to explore its relationship with lithologic features. They suggest that the relationship between color/sedimentological features/type of sediment must be considered with some caution, but also that this analysis is useful in characterizing/discriminating between different types of sediments combining with other parameters such as lithology, sedimentary parameters and ichnological variations. In addition, they state that a detailed ichnological analysis should accompany the sedimentological study of deep-sea modern cores in order to avoid misinterpretations in the sedimentological interpretation.

Kaboth et al. (2016) present a continuous high-resolution benthic foraminifera $\delta^{18}\text{O}$ record from the upper MOW core at Site U1386 within the Algarve basins for the last 150 kyr. They take an integrated approach, relating their results to glacial-interglacial induced sea level variations, Heinrich Events (HEs) and Sapropel (S) formation in the Eastern Mediterranean Sea. They also discuss how these climatic oscillations affected upper MOW variability in the past, how upper MOW core variations relate to changes in the lower MOW core at the same time, and how hydrographic changes within the Mediterranean Sea contributed to these variations over the last 150 kyr. They demonstrate that the influence of the upper core of the MOW was strongest during MIS 5 and MIS 1, coeval with similar variability in the Levantine Intermediate Water in the Mediterranean Sea. They found clear evidence for a vertical shift of the MOW from the upper to the middle slope of the Gulf of Cadiz during sea level lowstands coinciding with MIS 4 and MIS 2 but also during MIS 3. Their results also indicate an increased upper MOW flow correlated with Heinrich Events 7 to 10 and the Younger Dryas, and were inversely related to precession-forced monsoonal freshwater inputs into the Eastern Mediterranean.

4. Final considerations

The Gulf of Cadiz represents one of the world's premier contourite laboratories and thus offers an ideal testing ground for the contourite paradigm. Of the 5.5 km of core recovered during IODP Expedition

339 in the Gulf of Cadiz and west off Portugal, at least 4.5 km belongs to the Contourite Depositional System. Contourites are the most common sediment type, making up 95% of the Quaternary and about 50% of the recovered Pliocene succession. There can be no doubt that the IODP Expedition 339 results have more than met our initial scientific objectives (Expedition 339 Scientists, 2012, 2013; Hernández-Molina et al., 2013, 2014a, 2014b; Hodell et al., 2013; Stow et al., 2013a; Bahr et al., 2014, 2015; Balestra et al., 2015; Eynaud et al., 2016; Grunert et al., 2015; Hodell et al., 2015; Jiménez-Espejo et al., 2015; Lebreiro et al., 2015; Maiorano et al., 2015; Martín-García et al., 2015; Rodríguez-Tovar et al., 2015a, 2015b; Singh et al., 2015a, 2015b; Tzanova and Herbert, 2015; Tzedakis et al., 2015; van den Berg et al., 2015; Voelker et al., 2015; Sánchez Goñi et al., 2016; Turchyn et al., 2016; van der Schee et al., 2016; and the contributions in this volume).

Results from this Elsevier Virtual Special Issue (VSI) "Mediterranean Outflow" have regional and global implications on the understanding of the opening of the Gibraltar Gateway and onset of MOW, paleoceanographic and climatic changes, tectonic events and changes in global thermohaline circulation. Considering the main results that have emerged from contributions in this VSI, we highlight the following points:

- Many sediment cores were collected during Expedition 339 and, thus far, only a fraction of them have been studied in detail. Therefore, additional studies will surely provide new data to stimulate ideas and hypotheses in the coming years, which will be important for increasing our limited knowledge not only of deep marine processes, but also for bottom-currents and their associated oceanographic processes and products.
- Comparison between the main results obtained from IODP Expedition 339 with those from the adjacent Rharb, Guadalquivir Basins and Mediterranean Basins (e.g., CIESM, 2008; Roveri et al., 2014; Flecker et al., 2015) is essential for a better understanding of the interchange between the Mediterranean / paleo-Tethys and the Atlantic ocean in older geological periods (e.g., Miocene). In this regard, the support of the national oil companies and new drilling initiatives, such as the IODP proposal 771, currently with the IODP Operations Task Force (Hodell et al., 2014) and the IMAGE project (*Investigating Mediterranean-Atlantic Gateway Exchange*, Flecker et al., 2016), will be very important in the coming years for establishing more refined interpretation.
- Important conceptual implications should be considered. Tectonics represent an important factor acting on long time scales for controlling deep-marine sedimentation. Orbital-induced climate variations and sea level change are also significant on shorter timescales influencing sedimentation. It is important to test similar changes in other areas, in other drifts with a good age model for determining the specific cause-effect relationships between plate-tectonic configuration, climate and bottom-currents.
- The existing models for fine-grained contourites are found to be in good working order, but there is enormous variability in the spatial and temporal facies changes in contourite depositional systems. The results obtained during Expedition 339 are in agreement with the concept that there is a greater variety of facies sequences for bottom-current deposits than is currently represented in most existing contourite facies models (Shanmugam et al., 1993; Shanmugam, 2006, 2012, 2013; Martín-Chivelet et al., 2008; Mulder et al., 2013; Stow et al., 2013a, 2013b; Hernández-Molina et al., 2013; Hernández-Molina et al., 2016). Therefore, other sedimentary facies models need to be considered. Future detailed work on contourite sediments will allow us to better understand the nature of bottom-current processes and associated contourite deposition. This will improve our understanding of diagnostic criteria and facies recognition from other deep-water deposits (e.g. turbidites, hemipelagic or pelagites). Furthermore, it will provide advanced comprehension of the sedimentary budget for contourite drifts, their

sediments sources, and recognition of fossil contourites in the ancient record onshore. This new facies models should be included in current models for deep-water sedimentary record (e.g., Reineck and Shing, 1980; Pickering et al., 1989; Stow and Mayall, 2000; Nilsen et al., 2008; Rebesco and Camerlenghi, 2008; Hüneke and Mulder, 2011; Pickering and Hiscot, 2016).

- An enormous quantity and extensive distribution of contourite sands (and bottom-current-modified turbidite sands) has been reported, especially in the proximal part of the CDS close to the Strait of Gibraltar, where a very thick sandy contourite layer (> 10 m) was drilled that showed traction sedimentary structures. These sand deposits can potentially serve as reservoirs units, as well as muddy contourites that may function as hydrocarbon seals or source rocks and/or unconventional reservoirs (Viana, 2008; Rebesco et al., 2014). These represent a completely new and important exploration target for potential oil and gas reservoirs.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.margeo.2016.05.009>.

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