



## Virtual special issue on IODP expedition 339: The Mediterranean outflow

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### 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 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 (Hernández-Molina et al., 2015; Lofi et al., 2015; Ducassou et al., 2015; Alonso et al., 2015; Takashimizu et al., 2016; Nishida, 2015; Dorador and Rodríguez-Tovar, 2015a, 2015b; Kaboth et al., 2015). The *Global and Planetary Change* volume consists of 18 papers described below, 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. 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 study 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 targeted 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 also selected 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 (Hodell et al., 2013).

The extensive contourite depositional system (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; Hernández-Molina et al., 2003, 2006, 2011, 2014a, 2015; 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 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 as 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

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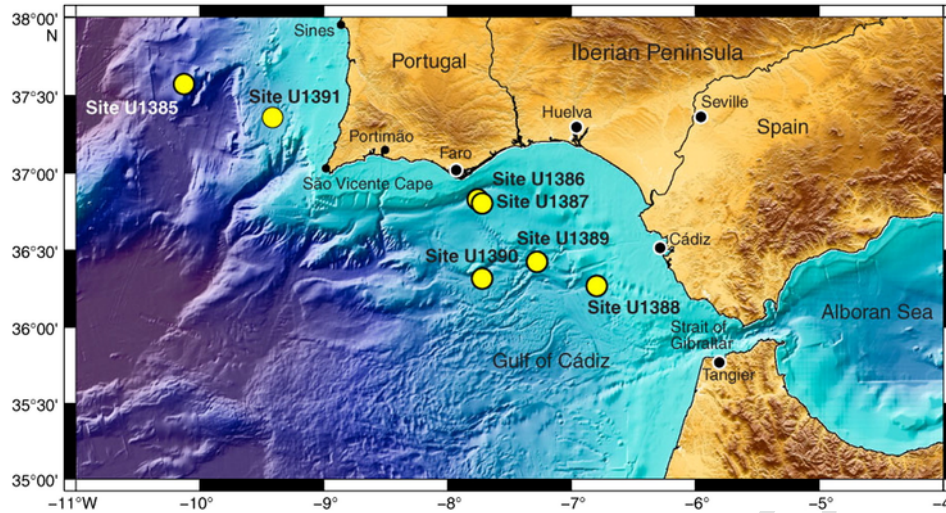


Fig. 1. Expedition 339 sites in the Gulf of Cádiz and West Iberian margin, shown as yellow solid circles.

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](http://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 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 Resolution 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 global and planetary change volume

This *Global and Planetary Change* volume contains 18 contributions. Eleven of the papers report on material (sediments and pore fluids) from Site U1385 (“Shackleton site”), which constitutes a complete record of hemipelagic sedimentation for the last 1.43 Ma (Marine Isotope Stage 47) with a mean sedimentation rate of  $9.2 \text{ cm kyr}^{-1}$ . Results from Site U1385 presented in this volume and elsewhere demonstrate the great promise of the site to study millennial-scale climate change and land–sea comparisons. Preliminary results from Expedition 339 showed the same surface climate signal recorded at the Shackleton site is also present in the contourite drift sites. However, sedimentation rates are 3–10 times greater in the contourites than Site U1385 (Expedition 339 Scientists, 2013), thereby providing the potential of even greater temporal resolution. Five of the presented papers use cores recovered from the contourite drifts in the Gulf of Cadiz and SW Iberian Margin, and focus particularly on the history of the MOW on short ( $10^3$  years) to long ( $10^4$  to  $10^6$  years) time scales. Two studies report results from cores collected nearby those recovered during Expedition 339 and are directly related to the expedition objectives.

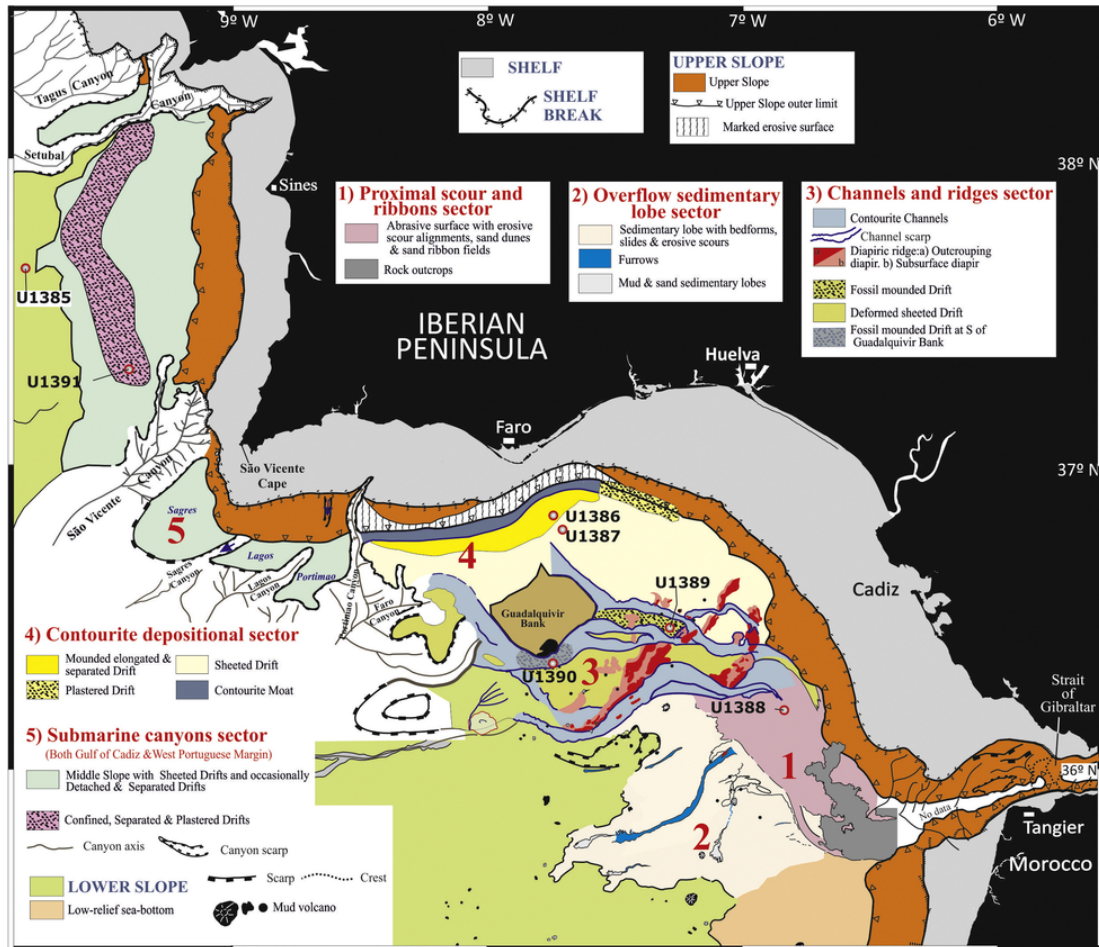
#### 3.1. Shackleton site papers

Hodell et al. (2015) provide the stratigraphic and chronologic framework for Site U1385 needed to underpin paleoceanographic studies of the Shackleton site. A verifiably composite section was constructed using core scanning XRF data to 166.5 m. An oxygen isotope stratigraphy was produced by correlating  $\delta^{18}\text{O}$  at Site U1385 to the LR04 stack. A strong precession signal in sediment color at Site U1385 provides an astronomically-tuned time scale and correlation to Mediterranean sapropel cyclostratigraphy. The Ca/Ti record (measured every 1-cm) provides a record of millennial-scale climate variability, which was a pervasive feature of glacial climates for the last 1.5 Ma of the Pleistocene. Each glacial onset was marked by a strong increase in millennial variability and, in contrast, each deglaciation was marked by a ‘terminal stadial event’ followed by an interglacial period when millennial variability was suppressed.

Eynaud et al. (2016) provide an important data set of understudied dinoflagellate cyst populations in cores from the Iberian Margin, Gulf of Cadiz and Alboran Sea. They compare dinoflagellate cysts from several of the past interglacials (MIS 1, 5, 11 and 19) at Site U1385. The dinocyst population were similar on both sides of the Strait of Gibraltar indicating a persistent interchange of populations between the Atlantic and Mediterranean even during sea-level low stands.

Sánchez Goñi et al. (2016) present grain size and physical property data at three sites from the Gulf of Cadiz (Sites U1388, U1389 and U1390) and compare results with pollen and oxygen isotopes at the Shackleton site (U1385) for two short intervals: MIS 31–30 and MIS 12–11. They found the interval from  $\sim 1.1$ – $1.05$  Ma (MIS 31–MIS 30) before the Middle Pleistocene Transition (MPT) was marked by wetter climate and weaker bottom current than the interval from 0.47–0.39 Ma (MIS 12–MIS 11), after the MPT. Stronger regional aridity during MIS 12 coincided with an increase in grain size interpreted to represent stronger MOW, supporting a link between aridification and MOW production.

Martin-Garcia et al. (2015) reconstruct past sea surface water conditions at Site U1385 for MIS 13 to 21 by analyzing planktonic foraminifer assemblages. They found that millennial-scale variability in Sea Surface Temperature (SST) occurred at both glacial onsets and terminations. Pronounced stadial events were recorded at all deglaciations when freshwater was released to the North Atlantic as ice sheets collapsed at glacial terminations. At the onset of glacia-



**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).

tions, SST along the Portuguese margin remained relatively warm whereas the surface waters of the North Atlantic experienced cooling, generating a large latitudinal SST gradient that may have increased zonal moisture flux to the growing ice sheets.

Tzedakis et al. (2015) provide evidence that North Atlantic millennial-scale climate variability extends to the 41-kyr world of the Early Pleistocene. Joint foraminiferal isotopic and pollen analyses at IODP Site U1385 during Marine Isotope Stage 38 (~1.26 Ma) shows the presence of millennial-scale variability in the coupled ocean–atmosphere–land system in the North Atlantic, providing the first direct evidence for the response of western Iberian vegetation to abrupt climate changes in the Early Pleistocene. The magnitude and pacing of climate change bears similarities to Dansgaard–Oeschger variability of the last two glaciations. A related study by Birner et al. (2016) confirmed that millennial variability in MIS 38 has a pattern similar to the bipolar seesaw of MIS 3.

Balestra et al. (2015) present a detailed study of calcareous nanofossil biostratigraphy at Site U1385 and correlate the nanofossil bioevents to the oxygen isotope stratigraphy of Hodell et al. (2015). The analyses provide further data on the stratigraphic distribution of selected species and genera resulting in new insights into the environmental control of their stratigraphic patterns. The exceptionally high carbonate content (expressed in physical and chemical properties of Site U1385) during interglacials MIS 9, 11 and 13 are related to the

abundance of the heavily calcified *Gephyrocapsa caribbeanica*, which was the most important producer of carbonate from MIS 14 through 8.

Maiorano et al. (2015) also studied coccolithophore abundances from the Shackleton site between MIS 16 and 10. The coccolithophore abundance mirrors the Ca/Ti pattern indicating that coccolith-derived carbonate is the dominant contributor to carbonate production in this interval. The study confirms a distinct increase in coccolithophore accumulation at the MIS 14/13 transition, which coincides with the beginning of a worldwide bloom of *G. caribbeanica* in the mid-Brunhes Chron. Coccolithophore populations also record millennial-scale cold events that are associated with decreases in productivity and increases in reworked taxa.

Grunert et al. (2015) present census counts of benthic foraminifera across Terminations I and II at Site U1385. A strong taphonomic bias is identified in recent (mudline) samples, whereby the shells of astorhizoid taxa (~80% of the present-day fauna) quickly disintegrate upon burial, leaving impoverished fossil assemblages. Nonetheless, variations in the benthic foraminiferal assemblages still reveal information about changing organic matter supply, deep-water oxygenation and temperature. Large changes in deep-water conditions occurred during the last two terminations. Heinrich stadials (HS) 1 and 11 were marked by low oxygen conditions coinciding with decreased water-temperature and lower benthic  $\delta^{13}\text{C}$ , pointing to the strong influence of a southern sourced water-mass during these periods.

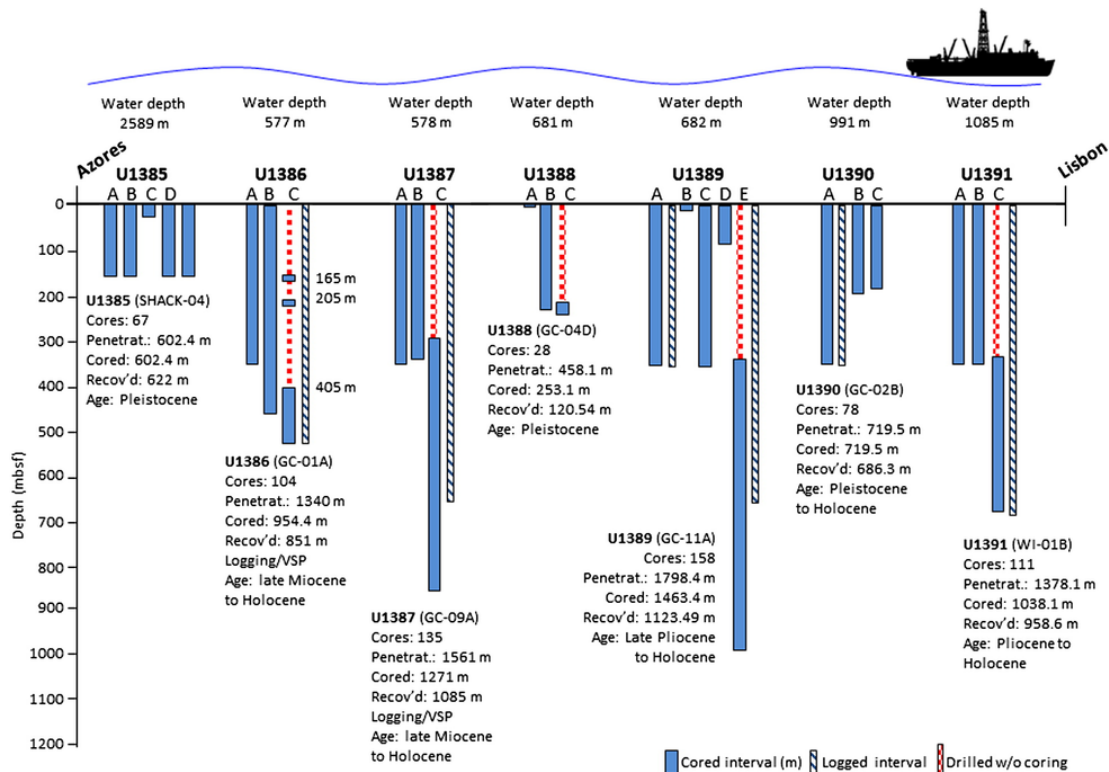


Fig. 3. Expedition 339 sites. 19 holes (681 cores) were drilled in 46.1 days with a penetration of 7857.4 m, cored 6301.6 m and recovered 5446.7 m (86.4%).

Rodríguez-Tovar et al. (2015a, 2015b) offer two papers detailing ichnological changes across the last five glacial terminations at Site U1385. The trace fossil assemblages generally indicate well-oxygenated bottom and pore-water conditions during interglacial as well as glacial stages, with episodic decreases in oxygenation at glacial terminations. Short climatic events occurred during Terminations 1, 2, 4 and 5, which induced a similar response of trace fossil and benthic foraminifera communities to variable input of food and oxygen availability. Terminations are generally marked by a deterioration of oxic conditions with increased export productivity and accumulation of sediment organic matter. The evolution of the macrobenthic trace-maker community responds to major changes in bottom water ventilation and food availability.

Turchyn et al. (in press) examine the pore water geochemistry at Site U1385 using dissolved sulfate concentrations and associated sulfur and oxygen isotope ratios. Sulfate reduction occurs in the uppermost 7 m of sediment followed by a 38-m interval where sulfate concentrations and isotopic values do not change significantly. Below this level, sulfate concentrations are depleted to zero and sulfur isotopes increase markedly between 45 and 55 m below seafloor. These results support that sulfite to sulfide reduction is the limiting step in microbial sulfate reduction, and that the isotope fractionation expressed in the residual pore water sulfate pool is inversely proportional to the net sulfate reduction rate.

### 3.2. Contourite site papers

Voelker et al. (2015) studied Site U1387 on the Faro Drift (559 m water depth) for the interval from MIS 29 to 34 (1020–1135 ka), which brackets the unusually warm interglacial MIS 31. This record illustrates the great potential of sites in the Gulf of Cadiz to study past changes in MOW and millennial climate variability beyond the reach of ice cores. On orbital time scales, the authors found insolation

maxima (precession minima) led to poor ventilation and a sluggish upper MOW core, whereas insolation minima were associated with enhanced ventilation and often also increased bottom current velocity. On millennial time scales, cold stadial events were associated with short-term maxima in flow velocity and better ventilation of MOW, similar to the response observed during MIS 3.

Singh et al. (2015a, 2015b) offer two studies from the Gulf of Cadiz. The first paper presents isotope and benthic foraminifer data from Site U1387 for the last 225 ka to study benthic paleoenvironmental conditions and the history of the upper core of MOW. They found that periods of weakened MOW correlate with deposition of sapropel layers of the Mediterranean Sea, implying strong coupling between glacial–interglacial climate and MOW circulation in the Gulf of Cadiz. The second paper reports changes in planktonic foraminiferal assemblages at Site U1391 from the SW Iberian margin for the last 900 kyr. The coldest conditions of the past 900 ka occurred during MIS 18, 20 and 22 when a polar/subpolar water mass invaded the study area, resulting in a situation similar to the present day Arctic Front. Prior to the Middle Brunhes Event (MBE), interglacial periods were relatively colder than those of the post-MBE period.

Tzanova and Herbert (2015) present an alkenone-based reconstruction of SST at IODP Site U1387 in the Gulf of Cadiz, which records paleoenvironmental conditions for Atlantic waters that flowed into the Mediterranean Sea during the Pliocene. The Pliocene surface waters of the Gulf of Cadiz and the Mediterranean Sea were as much as 7 °C warmer than the modern average of ~19–20 °C. The reconstructed temperatures show a ~1 °C cooling for the Atlantic side of the Strait of Gibraltar from ~6 Ma to ~2.7 Ma and increasingly cooler glacial periods. The long-term SST record from Site U1387 provides a basis for future studies into the hydrological balance of the Mediterranean and the temperature component of MOW density.

Lebreiro et al. (2015) used Pb and Sr radiogenic isotopes to trace water masses and sediment source changes at Site U1386 in the Early Pleistocene between 1.2 and 1.8 Ma. Results indicate a persistent cyclic pattern with MOW and fluvial deposition dominating during glaciations and Atlantic Waters and aeolian influence during interglacial periods. The authors suggest that shifts in ocean and atmospheric processes in the Gulf of Cadiz were strongly controlled by Earth's obliquity (41 kyr-cycle) and insolation at 35° N during the Early Pleistocene.

### 3.3. Other papers

Jiménez-Espejo et al. (2015) examined three marine sediment records spanning the last 20 kyr to trace intermediate waters along the Alboran Sea. They used redox-sensitive elements and the Nd isotopic composition of foraminiferal ferromanganese coatings to infer water mass provenance of the Eastern/Western Mediterranean. During deglaciation, higher Nd isotopic values and U/Th ratios point to an enhanced contribution of modified Levantine Intermediate Water (LIW). The Eastern water mass appears to have influenced shallower water depths in the Alboran Sea during the entire deglaciation and until the early Holocene. The authors speculate that the lower branch of MOW was dominantly controlled by high latitude climate variations, whereas the middle and upper branches were instead forced by low latitude processes, but more detailed studies are needed to test this hypothesis.

Van den Berg et al. (2015) present a Messinian cyclostratigraphic age model based on the Montemayor-1 core drilled in the Guadalquivir Basin in southern Spain. The geochemical records revealed a strong precession cycle that is used for astronomical tuning. After applying the new age model, the upper Messinian glacial stages and deglaciation were clearly identified in the oxygen isotope records of the Montemayor-1 core. This permitted a reinterpretation of existing planktonic and benthic oxygen isotope records for the core and comparison with equivalent successions in the Rifian Corridor in northern Morocco, resulting in a re-evaluation of the influence of the different water masses in the region. They observed no direct influence of MOW immediately before or during the Messinian Salinity Crisis.

### 4. Final considerations

The polar ice cores have provided superb records of past climate change that serve as the de facto “type sections” to which most late Pleistocene paleoclimate records are compared. However, the oldest continuous ice cores in Greenland and Antarctica are limited to the past ~124 and 800 ka, respectively. An important challenge for the paleoceanographic community is to recover complementary marine sections with sufficiently high sedimentation rates that can be used to reconstruct Pleistocene climate variability at high temporal resolution beyond the limits of the polar ice cores. During Expedition 339, we recovered sequences at multiple sites that are suitable for producing long records of millennial variability for the late Pleistocene. However, only a fraction of them have been analyzed in detail so far. Glimpses of the potential of these sequences are provided by papers in this volume and other publications (Voelker et al., 2015; Hodell et al., 2015; Tzedakis et al., 2015; Birner et al., 2016).

Results demonstrate the surface water signals (e.g., planktonic  $\delta^{18}\text{O}$ , alkenones) are similar between the Expedition 339 contourite (U1386-1391) and Shackleton (U1385) sites, whereas the benthic signals reflect variations in the properties of MOW and Northeast Atlantic Deep Water, respectively. A particularly powerful strategy will

be to directly correlate the surface water proxies among sites, and then compare the benthic proxies to identify contrasting changes in MOW and deep-water circulation in the Atlantic.

Although Expedition 339 has recovered a superb set of cores for high-resolution paleoclimate studies, additional drilling on the Iberian Margin is still needed to: 1.) extend the records beyond the base of Site U1385 (1.45 Ma) to the entire Plio-Pleistocene and latest Miocene; and, 2.) recover a full depth transect of sites spanning the range of the major subsurface water masses of the North Atlantic. Together with Expedition 339, the sites proposed by IODP Drilling Proposal 771 will constitute a complete depth transect from 566 to 4657 m on the eastern margin of the North Atlantic basin (Hodell et al., 2014). The sedimentary dip-sticks will permit a comprehensive reconstruction of past water mass variability in the North Atlantic through the Plio-Pleistocene, much of which appears to be related to spatial redistributions on both glacial-to-interglacial and millennial time scales. Understanding the role of the deep ocean in climate change is one of the missing keys for unlocking the underlying mechanisms of glacial-interglacial cycles and millennial-scale climate variation (Adkins, 2013). Another missing piece of the climate puzzle is how millennial- and orbital-scale climate variability interact to produce the observed patterns of Pleistocene climate change. In this regard, the sediment recovered during Expedition 339 will provide important reference sections for reconstructing the history orbital and suborbital climate variability during the Pleistocene.

### Uncited reference

Hüneke and Mulder, 2011

### Acknowledgements

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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.gloplacha.2016.06.016>.

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