New Advances in the Contourite Paradigm: IODP Expedition 339, Gulf of Cadiz

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Abstract: *IODP Expedition 339 cored over 4.5km of sediment from the Cadiz Contourite Laboratory. This provided a rigorous test for the contourite paradigm. The sediments are remarkably uniform in their mixed siliciclastic-bioclastic composition and textural attributes. They have a general absence of primary sedimentary structures, and an intense bioturbation throughout with a distinctive, small-scale, monotonous ichnofacies and local omission surfaces. Most sections are characterized by bi-gradational sequences from inverse to normal grading, but also include a range of partial sequences of which the base-cut-out sequences are most common. All these features are fully consistent with the established contourite facies model. Important refinements include the nature and significance of sandy contourites, the frequency of base-cut-out partial sequences, and the role of sediment supply.*

Key words: *Contourites, Gulf of Cadiz, IODP 339, facies models, contourite reservoirs.*

INTRODUCTION

IODP Expedition 339 drilled 5 sites in the Gulf of Cadiz and 2 off the west Iberian margin (Fig. 1). One of the principal scientific aims was to investigate the nature and effects of the bottom currents related to Mediterranean Outflow Water (MOW) on contourite deposition and erosion along the Iberian continental margin (Hernández-Molina et al, 2014). The region is informally known as the *'contourite laboratory'* on account of the many detailed studies made over the past four decades, and very clear documentation of bottom currents, contourite drifts, bedforms and erosional features (Stow et al, 2012). The complex architecture of alongslope deposits and erosion along this mid-slope region is known as a contourite depositional system (CDS) (Hernández-Molina et al, 2014).

The sites drilled on IODP Expedition 339 recovered around 4500 m of core through contourite drifts of the Cadiz CDS, at water depths between 570m and 1094m. This provides a rigorous testing ground for the existing contourite facies model (e.g. Stow and Faugères, 2008) and an opportunity to refine its detail as necessary. There is still controversy surrounding the validity of this model, and several authors have invoked rather different sedimentary characteristics for the recognition of ancient contourites exposed on land.

The Gulf of Cadiz straddles the diffuse boundary between the Eurasian and African plates, immediately west of the Straits of Gibraltar. The present-day circulation pattern in the region is dominated by the near-bottom outflow of warm, highly saline MOW and the turbulent inflow of less saline, cool-water mass of the Atlantic Inflow Water at the surface. The MOW forms a strong bottom current flowing towards the W and NW above North Atlantic Deep Water. Interaction of this bottom current with the slope topography has led to construction of the Cadiz CDS over the past 4.5My.

RESULTS

The recovered section ranged in age from Holocene to Pliocene at every site, and penetrated into the uppermost Miocene at two sites. Mean sedimentation rates were generally high for all contourite-dominated Holocene-Pleistocene intervals, compared with typical rates for open ocean slope systems. They ranged from 25-100 cm/ky for the Cadiz sites, with the more rapid rates being more proximal to the Gateway, and from 10-15 cm/ky on the west Portuguese margin plastered drift at site U1391. Mean rates for the Pliocene were very variable, ranging from 5-20 cm/ky, but considerably affected by non-depositional and erosional hiatuses.

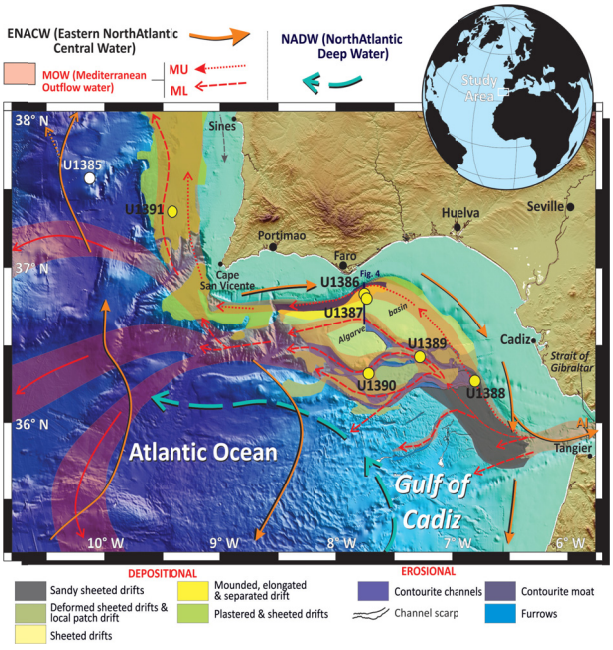

FIGURE 1. Gulf of Cadiz Continental Margin showing IODP Expedition 339 sites and track of Mediterranean Outflow Water.

The principal facies recovered through the contourite drift succession include calcareous muds, silty muds, muddy sands and silty sands. We are confident in their interpretation as contourites for the following reasons: (a) they occur in mounded, sheeted and plastered drifts clearly identified in comprehensive seismic datasets from the region; (b) these drifts are closely aligned with the known passage of MOW bottom currents; (c) the elevated position of all sites away from the passage of downslope processes, for most of the Pleistocene-Holocene; (d) the elevated and completely isolated position of two sites, which precludes the possibility of turbidity current access; and (e) the many previous studies of the present-day seafloor and topmost sediments, which all concur with a contourite aspect of the sediment facies.

For clarity, therefore, we refer to these facies as: muddy contourites, mud-silt contourites, muddy sand contourites, and silty sand contourites. Holocene and later Pleistocene (post 1 Ma) sedimentation was everywhere dominated by contourites, with < 5% clearly turbidite intercalation evident in the sites to which turbidity current access was possible. Prior to 1 Ma during the earlier Pleistocene and Pliocene, turbidites, debrites and slump deposits were more common. Where recovered, the Miocene mainly comprised normal slope hemipelagic sedimentation.

Contourite characteristics

One of the most typical aspects of the Cadiz contourite sedimentation is its *uniformity* throughout: the dominance of greenish grey colour, the general absence of primary sedimentary structures, the sediment homogenization by bioturbational mottling, and the uniformly mixed biogenic-terrigenous composition. There is also consistent cyclicity of facies and grain size in bi-gradational units.

They have a general absence of primary sedimentary structures, except for a somewhat discontinuous and widely-spaced silt lamination within muddy contourites that show the highest rates of sedimentation. There is an intense, continuous bioturbation throughout with a distinctive, small-scale, monotonous ichnofacies and local omission surfaces. Most sections are characterized by bi-gradational sequences from inverse to normal grading, but also include a range of partial sequences of which the base-cut-out sequences are most common.

Taking the total number of measured sequences at each site and the time interval over which they were deposited yields an average cyclicity of 1/6000 y. This ranges from 1/4000 y to 1/8000 y. The actual cycle period may be a little less if we take into account 'hidden' sequences within the mud-rich sections.

The grain size is mostly fine and with poor to moderate sorting for the majority of drift contourites – in the clay, silt and very fine sand range. Coarser bioclastic material is typically in or nearly in situ. The sandy contourite layers range from fine-grained and muddy, with rare well-sorted intervals. Within these sands, there is often scattered coarser-grained and fragmented bioclastic debris. Some of the thicker-bedded sandy contourites in the most proximal site are cleaner and moderately well-sorted fine-medium sands.

Total organic carbon content varies between < 0.3% and 1.5%, with a C/N ratio that implies a general dominance of a marine over terrestrial source, but with some local variation. For most of the Pleistocene-Holocene period, the microfossil assemblage indicates relatively high organic matter supply.

Contourite sands

Spatial distribution of the contourite elements along the Cadiz continental margin are closely linked with the decrease in bottom-current speed down-flow from the exit of the Gibraltar Gateway. The rocky substrate west of Gibraltar gives way to an extensive contourite sand sheet, which extends along a mid-slope terrace for approximately 100 km before diverging into several contourite channels around the prominent seafloor relief created by mud volcanoes and diapiric ridges.

Seismic data and one industry borehole indicate that this sand sheet is at least 800 m thick. Site U1388 penetrated 220 m into this proximal sand sheet before the hole became too unstable to continue. Initial results indicate rapidly-deposited, late Quaternary, sandy contourites are dominant. The areal extent and vertical thickness of clean contourite sands display ideal reservoir characteristics and are therefore especially significant for the oil and gas industry. Deliberate search for this new style of deepwater succession could represent a paradigm shift for oil and gas exploration.

DISCUSSION

Following rigorous testing on over 4.5km of core recovered from the Cadiz continental margin, the existing contourite models (Stow and Faugères, 2008) are found to be in good working order. Some important refinements include the nature and significance of sandy contourites, the frequency of base-cut-out partial sequences in addition to the dominant bi-gradational sequence, and the role of sediment supply as well as bottom current velocity in determining the sequence type and frequency.

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