Looking for clues to paleoceanographic imprints: A diagnosis of the Gulf of Cadiz contourite depositional systems

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ABSTRACT

A new morphosedimentary map of the Gulf of Cadiz is presented, showing the contourite depositional system on the gulf's middle slope. This map is constructed from a broad database provided by the Spanish Research Council and the U.S. Naval Research Laboratory. Our map shows that this contourite depositional system comprises five morphosedimentary sectors: (1) proximal scour and sand ribbons; (2) overflow sedimentary lobe; (3) channels and ridges; (4) contourite deposition; and (5) submarine canyons. The Gulf of Cadiz contourite depositional system stems directly from the interaction between Mediterranean Outflow Water and the seafloor; its morphosedimentary sectors are clearly related to the systematic deceleration of the Mediterranean Outflow Waters westward branches, bathymetric stress on the margin, and the Coriolis force. The slope's depositional system can be considered as a mixed contourite and turbidite system, i.e., a detached combined drift and fan.

Keywords: contourite depositional system, middle slope, drifts, channels, diapirs, Gulf of Cadiz.

INTRODUCTION

Since the 1980s, research has confirmed the essential role of contourite processes in marine environments, to the point that the current conventional view is that the continental margins are built up by the combined action of downslope and along-slope sedimentary processes. When the along-slope processes dominate, they can generate contourite depositional systems. We use a new data set to describe, from a regional morphosedimentary point of view, the contourite depositional systems on the middle slope of the Gulf of Cadiz as a single system (Fig. 1). In this unusual system, along-slope processes are clearly dominant with regard to interaction between Mediterranean Outflow Water and the seafloor. Our study used a broad database collected since 1989, obtained during several cruises and projects, comprising bathymetric, side-scan sonar imagery, seismic data, and core data (Fig. 2).

MEDITERRANEAN OUTFLOW WATER: THE OCEANOGRAPHIC SCENARIO

The Gulf of Cadiz's present-day circulation pattern is characterized by intense oceanographic dynamics controlled by the exchange of water masses through the Straits of Gibraltar (Fig. 1). This exchange is determined by the highly saline and warm Mediterranean Outflow Water (MOW) near the bottom and the turbulent, less saline cool-water mass of Atlantic Inflow Water on the surface. Mediterranean Outflow Water forms a strong contour current moving from the southeast to the northwest along the middle slope above the North Atlantic Deep Water (Zenk, 1975). After passing the Gibraltar seamount, the Mediterranean Outflow Water forms a turbulent flux ranging from 150 to 200 m wide, which moves along a straight channel in a west-southwest direction at a speed of >200 cm/s (Ambar and Howe, 1979). Thereafter, the Mediterranean Outflow Water spreads westward into the Gulf of Cadiz and progressively sinks northwestward, descending the continental slope from a depth of 300 m because of the dense water's gravity-driven currents. The outflow water loses contact with the seafloor at 1000 m depth in the east sector and at 1400 m depth in the west sector.

As the Mediterranean Outflow Water moves westward, its temperature, salinity, and velocity decrease, and it divides into two main branches (Madelain, 1970; Ambar and Howe, 1979), the Mediterranean Upper Water and Mediterranean Lower Water. The Upper Water forms the upper core, moving as a warm flux between depths of 500 and 800 m at the base of the upper slope until Cape San Vicente is reached. The mean velocity is ~46 cm/s. The Mediterranean Lower Water constitutes the more saline, lower core and the Mediterranean Outflow Waters principal volume, at a depth of ~750–1200 m and with a mean velocity of ~20–30 cm/s. Mediterranean Lower Water is affected by the slope morphology, and divides into three minor branches between the Cadiz and Huelva meridians (Madelain, 1970; Melières, 1974): (1) the Intermediate Branch, which moves northwestward through the Diego Cao channel; (2) the Principal Branch, which is generated in the southern part of the Guadalquivir Bank that modifies the flux toward the southeast; and (3) the Southern Branch, which follows a steep valley toward the southwest.

CONTOURITE DEPOSITIONAL SYSTEM

The slope's main physiographic features are a shelfbreak located between 100 and 140 m depth; a steeper (2°–3°) upper slope between 150 and 400 m depth; and two gently dipping (>1°) wide terraces located at water depths of 500–750 and 800–1200 m on the middle slope, having a central sector with channels and ridges that trend northeast and a smooth lower slope (1°–0.5°). The contourite depositional system is located on the middle slope, and comprises the five major morphosedimentary sectors detailed next (Figs. 3 and 4).

Proximal Scour and Sand-Ribbons Sector

Located in the southeast area close to the Straits of Gibraltar, this sector was first defined by Kenyon and Belderson (1973). Erosive features, mainly erosive scour alignments and an abrasion surface, are dominant, but depositional features, such as extended sand dunes and sand-ribbon fields, have also been identified, especially in the northwest zone.

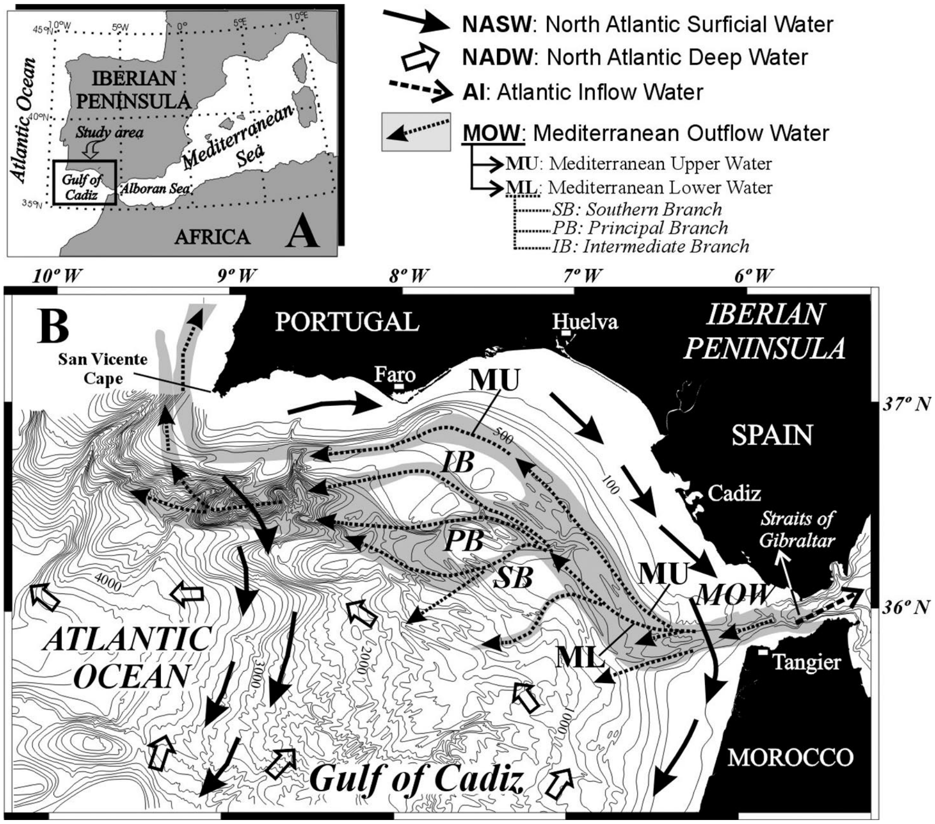

Figure 1. A: Location of Gulf of Cadiz. B: Regional bathymetric map indicating general circulation patterns of Mediterranean Outflow Water. Contours in meters.

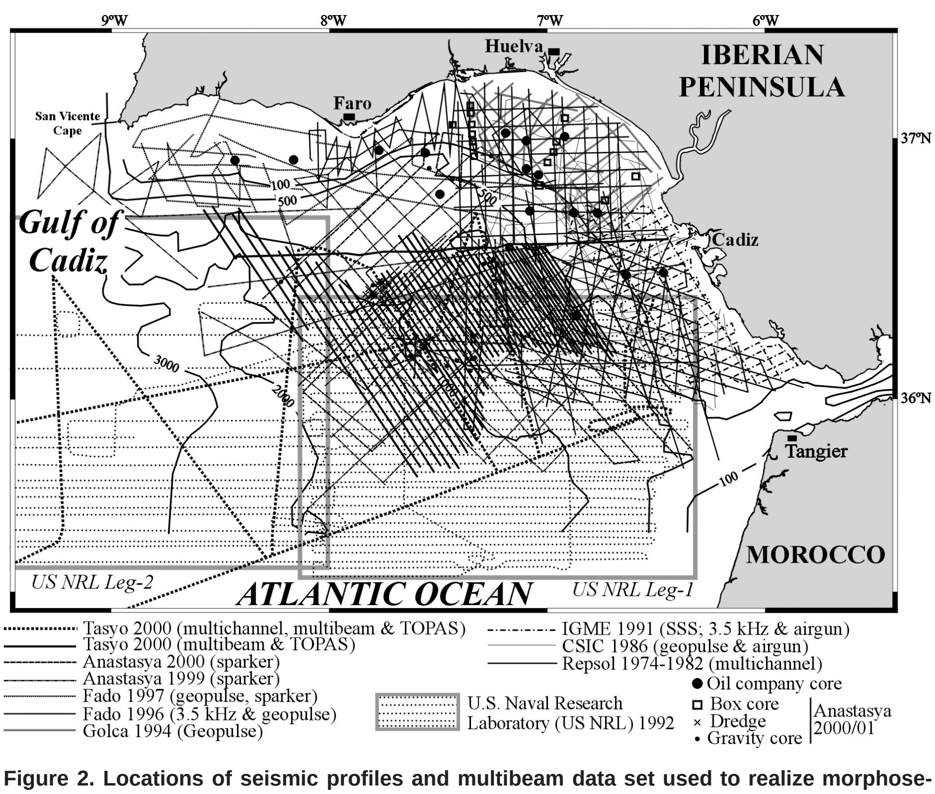

Figure 2. Locations of seismic profiles and multibeam data set used to realize morphosedimentary map. Contours in meters. IGME—Instituto Geologico y Minero de España. CSIC—Consejo Superior de Investigaciones Cientificas.

Overflow Sedimentary Lobe Sector

This sector is adjacent and seaward of the proximal scour and sand-ribbons sector, at a water depth of 750–1600 m, and has a fan shape opening up downslope in the south. It is very complex, owing to the effects of depositional, gravitational, and erosive processes, and consists of a megasedimentary lobe with bed forms and erosive scours. The most important sedimentary features are sand and mud sedimentary lobes and sand and mud wave fields. Noteworthy erosive features include several furrows that trend northeast. The largest (55 km long, 0.8–1.7 km wide), the Gil Eanes channel, was first described by Kenyon and Belderson (1973). Northward, the smallest channel, 16 km long and 0.8–2.3 km wide, is parallel to it. Gravitational processes, such as slides, are also frequent. This sector was partially studied previously (Kenyon and Belderson, 1973; Nelson et al., 1993).

Channels and Ridges Sector

This sector, located in the central area, was studied partially by Nelson et al. (1993), and described in detail by García (2002). Today it is dominated by erosive features on the seabottom, and five main contourite channels have been characterized. They are known as the Cadiz, Guadalquivir, Huelva, Diego Cao, and Gusano channels. These channels are S shaped, their along-slope zones trend northwest, and their downslope zones trend northeast. They are marked by some structural relief features, e.g., the Cadiz and Guadalquivir diapiric ridges and the Guadalquivir Bank. The channels are asymmetrical, generally presenting a deeper north flank; their lengths range from 10 km to $>$100 km, and they are 1.5–10 km wide with $\sim$10–350 m of incision. The Cadiz channel is the biggest and the most important, and within it, two recent steep 100–200-m-deep incisions have been identified, a consequence of overexcavation processes by the current. Contourite channels are located on the southeast flank of the diapiric ridge; however, many marginal valleys, with irregular morphology and a northeast trend, have been detected on the diapiric ridge's northwest flank. All of these erosive features were established over a relict contourite depositional sector, composed of relict separated mounded and sheeted drifts, affected by tectonics and diapiric phenomena.

Contourite Deposition Sector

This sector is located in the central and northwest areas. Sedimentary processes are dominant, and the middle slope is built up by two kinds of contourite deposits, elongated and separated mounded drift and sheeted drift. The Faro-Albufeira contourite system has been studied previously (e.g., Gonthier et al., 1984; Llave et al., 2001, among others), and is the largest morphosedimentary feature, comprising five morphological elements. From the upper to the middle slope these are the erosional surface on the upper slope; the Alvarez Cabral moat (80 km long and 4–11 km wide); the Faro-Albufeira elongated and

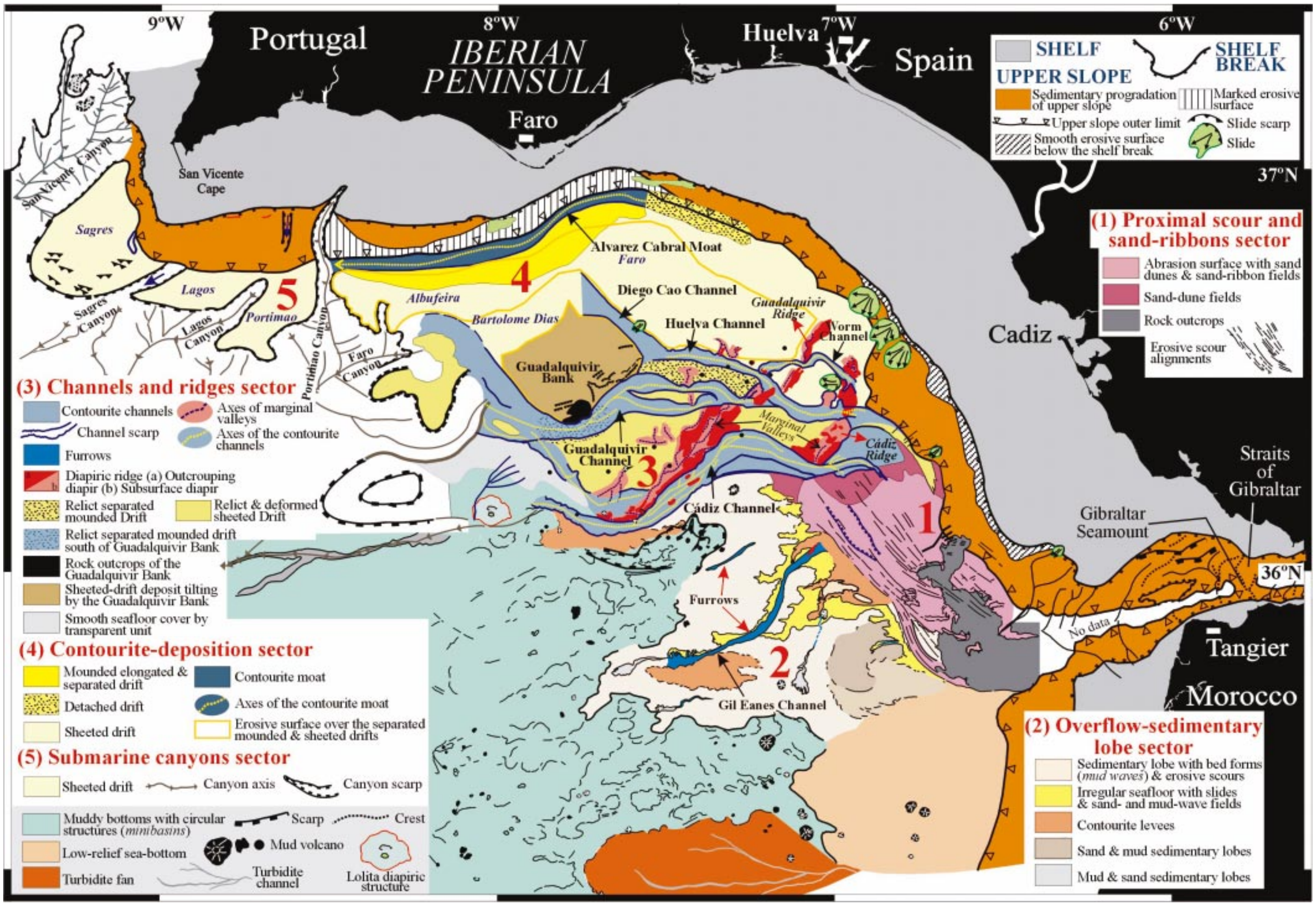

Figure 3. Morphosedimentary map of contourite depositional system on middle slope of Gulf of Cadiz. Sedimentary deposit types and bed forms are shown for five morphosedimentary sectors.

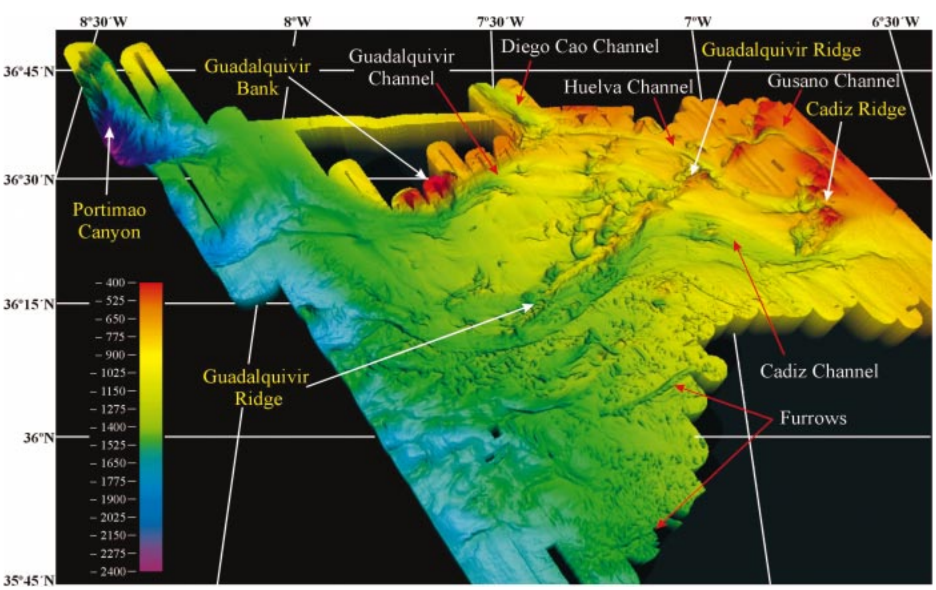

Figure 4. Three-dimensional model from swath bathymetry of central sector of middle slope of Gulf of Cadiz contourite depositional system, showing main contourite channels and furrows and main diapir ridge, with northeast trend. Scale bar is in m.

separated mounded drift (80 km long, 12 km wide, 600 ms thick); the Faro-Cadiz and Bartolome Dias sheeted drifts; and erosional features over the drift. Toward the east, before the Faro-Albufeira system, a detached drift (35 km long, 12 km wide, and 100 ms thick) has been determined in the transition between the upper and middle slopes.

Submarine Canyons Sector

Located in the western area, this sector is characterized by the Portimao, Lagos, Sagres, and San Vicente submarine canyons, which separate, from east to west, the Portimao, Lagos, and Sagres sheeted drifts.

DISCUSSION: LOOKING FOR CLUES TO PALEOCEANOGRAPHIC IMPRINTS

The Gulf of Cadiz contourite depositional system is a direct consequence of Mediterranean Outflow Water interaction with the sea-bottom along the middle slope. Its development is conditioned in part by Pliocene-Quaternary tectonics, resolved by the formation of regional curvatures on the margin surface and faults and diapiric structures related to local movements. Although different specific parts of this depositional system have been studied previously by others, it has never been approached comprehensively as a single unique system. Therefore, the defined morphosedimentary sectors should be related to the margin's bathymetric stress, the systematically decreasing speed of the different undercurrent branches as they move westward, and the Coriolis force.

The proximal scour and sand-ribbon sector, as postulated by Kenyon and Belderson (1973), results from the Mediterranean Outflow Water's strongly turbulent current that contours the slope after its entrance into the Gulf of Cadiz. In this sector, the Mediterranean Outflow Water's high velocity generated the abrasion surfaces and erosive scour alignments, but as current velocity decreases, sand ribbons and wave fields can be developed. We suggest that when the Mediterranean Lower Water interacts with local diapiric ridge structures, a deflection of the main flux could be produced, generating a small downslope turn of a filament from the principal flux and leading to the genesis of the northeast-trending furrows, and the genesis of the overflow sedimentary lobe. The overflow sedimentary-lobe sector is very complex, and has fan-shaped deposits. This megalobe could be the result of the overflow of the Mediterranean Lower Water's small downslope-turn filaments, but the deposits could also be due to the occurrence of many slides triggered by the tectonic structures.

The Mediterranean Upper Water and Mediterranean Lower Water fluxes are moving northwestward, producing the northwest-trending along-slope contourite channels at the beginning of the channels and ridges sector (Fig. 3). The Mediterranean Upper Water is flowing northwestward toward the contourite-deposition sector, as a tabular water mass along the toe of the upper slope on a terrace at a water depth of 500–800 m. It generates the slope's largest sheeted drifts (Faro, Albufeira, and Bartolome Dias). When the Mediterranean Upper Water flux interacts with the concave shape of the margin, it forms a detached drift in the transition between upper and middle slope. It then begins to erode the slope to the east of Faro coast. In this region, Mediterranean Upper Water becomes channeled and forms the slightly sinuous Alvarez Cabral moat. Because of the Coriolis force, causing the Mediterranean Upper Water current to shear to the right, the flow tends to erode the channel's right flank and to create the Faro-Albufeira elongate and separated mounded drift on the left side, where the current slacks. After the Portimao Canyon, the presence of the Portimao, Lagos, and Sagres sheeted drifts suggests the action of a new tabular flux of the Mediterranean Upper Water.

The Mediterranean Lower Water also flows northwestward along a deeper 800–1200 m terrace, and when it reaches the linear northeast-trending Cadiz and Guadalquivir diapiric ridges, the contourite channels change abruptly from their northwest trend to the new downslope southwest trend (Fig. 4). Consequently, an important increase of the current velocity in this area was determined by Nelson et al. (1993). With our new multibeam data, it is now possible to determine (1) that channels are not only present on the southern flank of the diapiric ridge; (2) that these asymmetrical channels have an S shape owing to the northwest trend in those areas lacking the structural control of the ridge; and (3) that these channels have a southwest trend when the linear diapiric ridges are present. Therefore, the occurrence of the marginal valleys on the north flank of the diapiric ridge is also important. This finding is noteworthy because the discovery of a secondary circulatory flux downslope, after Mediterranean Outflow Water passes the ridge, would enable us to better understand the genesis of these erosive features, and consequently the Mediterranean Outflow Water's regional hydrodynamic model would have to be revised. Because of the ridges, the Mediterranean Lower Water is divided into several minor branches. The Southern Branch is related to Cadiz channel, the Principal Branch could generate the Guadalquivir, Huelva, and Gusano channels, and the Intermediate Branch could generate the Diego Cao channel.

Several features could be related to the more recent tectonic activity that is responsible for the broad northwest-southeast compressional regime, such as the reactivation of the diapiric ridges. This recent tectonic activity could have increased and changed the submarine bottom relief and, consequently, controlled changes in the distribution of the currents. Therefore, the more recent tectonic activity could have conditioned several features, including (1) the recent origin of the channels and ridges sector, (2) the inactivity of the relict, elongated and separated mounded and sheeted drifts, (3) the recent genesis of the Diego Cao channel proposed by Llave et al. (2001), and (4) the recent overexcavation of the Cadiz channel related to movements of the diapiric ridges. In addition, the principal features over the middle slope are erosive at present, including the contourite deposition sector, in which an extant superficial erosional feature over the drift has been described (Llave et al., 2001). Therefore, these data support the proposals that one of the Mediterranean Outflow Water's major erosive events is related to highstand stages, such as the present one, that these erosive events represent a winnowing stage, and that the major depositional features, i.e., the drifts, are currently inactive on a regional scale. So, from the seismic analysis of the Quaternary sedimentary record, a second major erosive event should be considered at the end of the lowstand stage (Llave et al., 2001).

CONCLUSIONS

The contourite depositional system of the Gulf of Cadiz could be considered as a mixed contourite and turbidite system, a companion drift fan associated with the western North Atlantic margin (Faugères et al., 1999). However, the Gulf of Cadiz contourite depositional system does not fit into that model, because the contourite processes are dominant on the middle slope, and downslope processes dominate the lower slope and continental rise. These processes do not interact simultaneously, as in the North Atlantic margin model. We could call this system a detached combined drift fan, considering the margin's sedimentary stacking pattern, opposite to the pattern on the Hatteras or Hebrides margins, where the along-slope processes developed in a more distal part of the mixed system. Conventional wisdom now holds that the largest drift deposits tend to develop in marine basins. However, as indicated herein, many kinds of deposits could compose a contourite depositional system, and much research remains to be done to determine in detail the genesis and relationships of the sedimentary facies. A contourite depositional system can be formed by drift deposits, but also by sedimentary wave fields, channels, moats, furrows, scours, levees, sand ribbons, and sedimentary lobes. All of these deposits could, taken together, be considered clues to the paleoceanographic imprints related to the same water mass, but they could also be individualized, mainly due to the local behavior of the current due to seabottom stress, producing branches of the current, secondary flow, filaments, internal waves, local turbulence, overflows, helicoidal flow, and other features.

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