THE GULF OF CADIZ:
EXAMPLE OF AN UNSTABLE GIANT CONTOURITIC LEVEE

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The Gulf of Cadiz represents the pathway of a strong, warm (13°C) and saline (> 37 $g.l^{-1}$) bottom current called the Mediterranean Outflow Water (MOW). This flow comes out of the Mediterranean and spreads in the mid-depth North Atlantic at water depths of 500-1500 m. Its velocity is > 3 $m.s^{-1}$ when it flows out of the Strait of Gibraltar and decreases downstream for reaching a few $cm.s^{-1}$ seaward of the Cape St. Vincent (southwest Portugal). The MOW is at origin of the gravelly material found near Gibraltar and construction of many silty to clayey contouritic drift distaly.

New high-resolution bathymetry and imagery data were collected during the CADISAR cruise on the RV Le Suroît (August 2001) using a multibeam echosounder EM300. At the exit of the Strait, the MOW can be either channelled by major or secondary channels, or spill over a sedimentary levee. The high-sedimentation rate associated with the frequent earthquakes and the constant shearing by the water current generate overspread sediment deformation and instability. At the mouth of secondary channels, sediment accumulates as small sandy lobes. Depositional and erosional features show the major influence of the seafloor morphology on the MOW dynamics. These observations suggest that the Gulf of Cadiz system shares many similarities with channel-levee complexes formed by turbidity current activity. The main difference is that in the Gulf of Cadiz, the main process is a contour current interacting locally with gravity processes occurring in channels and valleys dissecting the continental slope.

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The Gulf of Cadiz is located in the eastern Atlantic Ocean, northwest of the Strait of Gibraltar, along Spanish and Portuguese margins (*figure 1*).

The Gulf of Cadiz represents the pathway of a strong, warm and saline bottom current called the Mediterranean Outflow Water (MOW) (see details in *PART 1*).

This flow comes out of the Mediterranean Sea and spreads in the North Atlantic Ocean at water depths of 500-1500 m (*figure 1*).

The MOW is at the origin of the gravelly material found near Gibraltar and construction of many silty to clayey contouritic drift distaly.

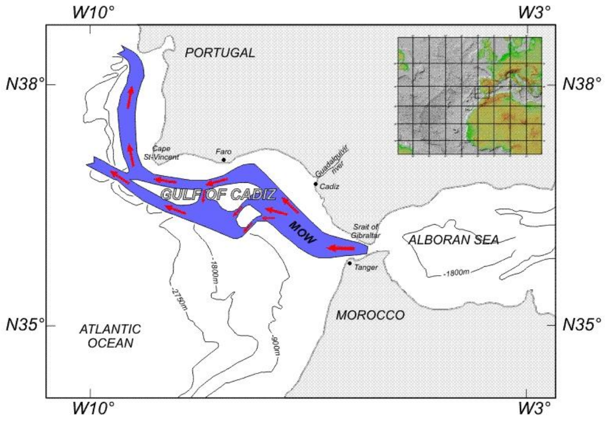

Figure 1: Gulf of Cadiz and MOW location (*after Madelain, 1970*).

New high-resolution bathymetry and imagery data were collected during the CADISAR cruise (August 2001) using a multibeam echosounder EM300 (see details in *PART 2*).

The area mapped during the CADISAR cruise covers a zone located between N35°40'/N36°30' and W6°30'/W8°10' (see details in *PART 3*).

Interpretation of data allowed the recognition of 14 morpho-sedimentary facies, and the identification of sedimentary figures and erosive structures along the path of the MOW cores (see details in *PART 4*).

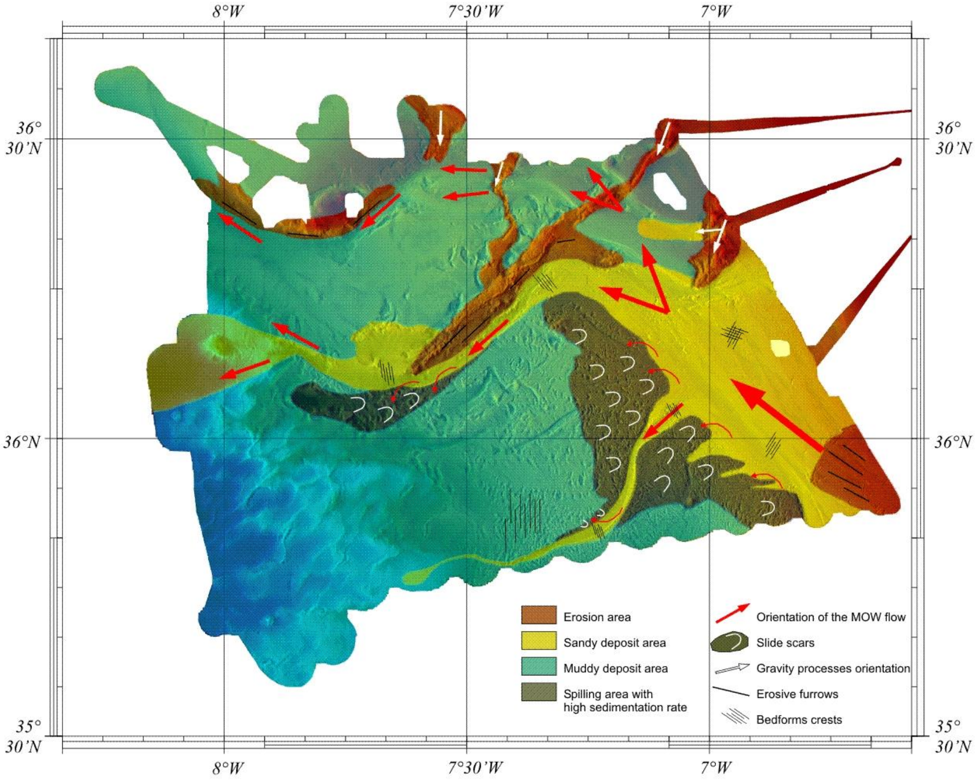

Figure 2: conceptual model of the MOW circulation in the Gulf of Cadiz.

Downstream of the Strait of Gibraltar, the MOW can be either channeled by major or secondary channels, or spill over a sedimentary levee (*figure 2*, see details in *PART 5*).

The high sedimentation rate associated with the frequent earthquakes and the constant shearing by the water current generate overspread sediment deformation and instability (*figure 2*, see details in *PART 5*).

At the mouth of secondary channels, sediment accumulates as small sandy lobes (*figure 2*).

Depositional and erosional features show the major influence of the sea floor morphology on the MOW dynamics (*figure 2*).

These observations suggest that the Gulf of Cadiz is a giant complex deep-sea contouritic system that present some similarities with channel-levee complexes formed by turbidity currents (feeder channels, channel shape, levee built by spill over, fluid activity, instability of levee flank, sediment waves, particle segregation).

The main difference is that in the Gulf of Cadiz, the main process is a contour current interacting locally with gravity processes occuring in channels and valleys dissecting the continental slope.

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PART 1 - REGIONAL SETTING

The Gulf of Cadiz (*figure 1*) is located in the eastern part of the Atlantic Ocean, between the African and Eurasian plates. It spreads of the Strait of Gibraltar (Spain) as far as Cape St-Vincent (Portugal) with an orientation NW/SE.

Tomographic data (Bijwaard and Spakman, 2000) and the recent SISMAR cruise (Gutscher and al., 2002) evidenced the presence of a accretion prism with a slip surface at approximately 10 km below seafloor. The existence of this prism is consistent with the recent discovery of numerous mud volcanoes, tectonically active since the Miocene (Gardner, 2000). Important earthquakes (e.g. Gorringe in 1969) show a significant present tectonic activity.

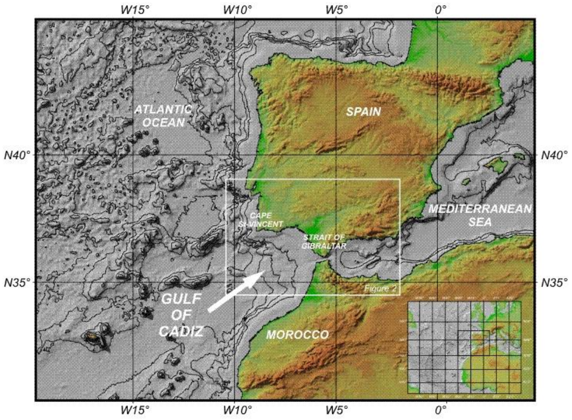

Figure 1: localisation of the Gulf of Cadiz (*Sismer database*).

At present, circulation on the Gulf of Cadiz margin is controlled by the exchanges between the Atlantic inflow (black arrows, *figure 2*) and a permanent flow of deep water flowing of the Mediterranean Sea towards the Atlantic Ocean called Mediterranean Outflow Water (MOW) (red arrows, *figure 2*).

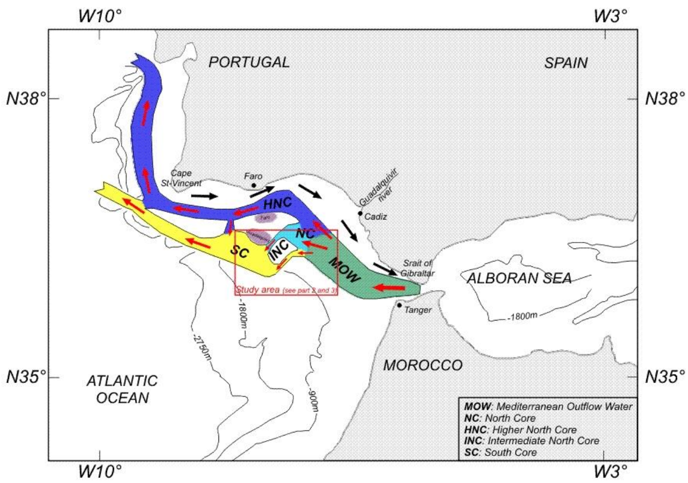

Figure 2: system of currents in the Gulf of Cadiz.

The Atlantic inflow circulates between 0 and 500 m of water depth and currently controls sedimentation on the continental shelf.

The MOW, strong counter-current, has been active since the Pliocene. It flows along the continental slope between 500 and 1500 m of water depth. At the exit of the Strait of Gibraltar, the MOW is deflected northward by the Coriolis force. Westward, the margin morphology induces the apparition of several flows (NC, HNC, INC and SC, *figure 2*).

The present sedimentation in the Gulf of Cadiz is controlled by the MOW. This is attested by the construction of large contourite drifts (e.g. Faro and Guadalquivir drifts, *figure 2*). The construction of these drifts is cyclic and controlled by climatic and eustatic oscillations (Faugères and al., 1985b).

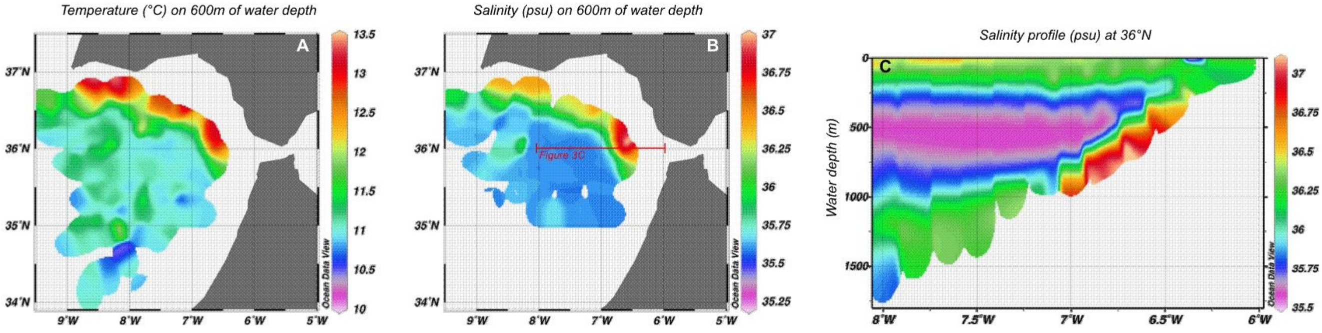

Figure 3: thermo-haline signature of the MOW in the Gulf of Cadiz.

Presently, the MOW is characterized by a temperature in the vicinity of 13°C (*figure 3A and 3C*), a high salinity (36.5 ‰; *figure 3B and 3C*), and a oxygenation of 4 ‰ (Madelain, 1970; Ambar and Howe, 1979a and b).

The MOW speed is up to 3 m/s^{-1} just out of the Strait of Gibraltar; this velocity decreases downstream from the Strait and reaches a few cm/s^{-1} seaward of the Cape St-Vincent. This gradient of velocities generates a particule sorting: coarse sediments (gravel and sand) in the more proximal parts of Gibraltar, and fine material (silt and clay) more distally.

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PART 2 - THE CADISAR CRUISE

Data have been collected in the Gulf of Cadiz during the CADISAR cruise on the RV "Le Suroît" in august 2001. Bathymetry (*figure 1*) and imagery (*figure 2*) have been acquired using the SIMRAD EM300 multibeam echosounder. Dataset have been completed by deep-towed acoustic system (SAR), low-frequency sediment echosounder (Chirp), sparker high-resolution seismic and 25 Kullenberg cores.

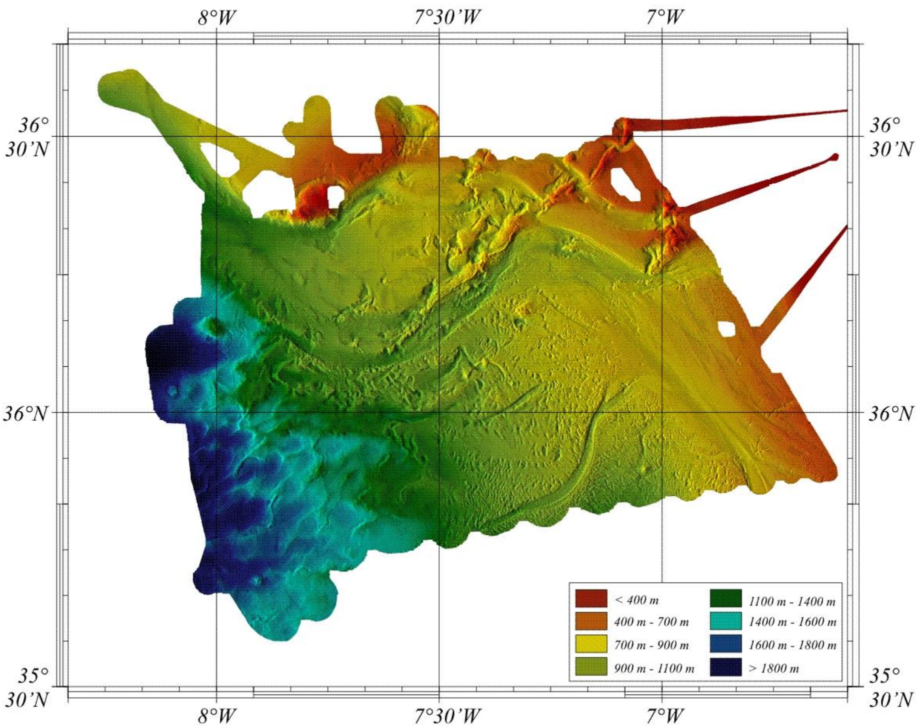

Figure 1: high resolution EM300 bathymetric map of the study area (see location on *figure 2, PART 1*).

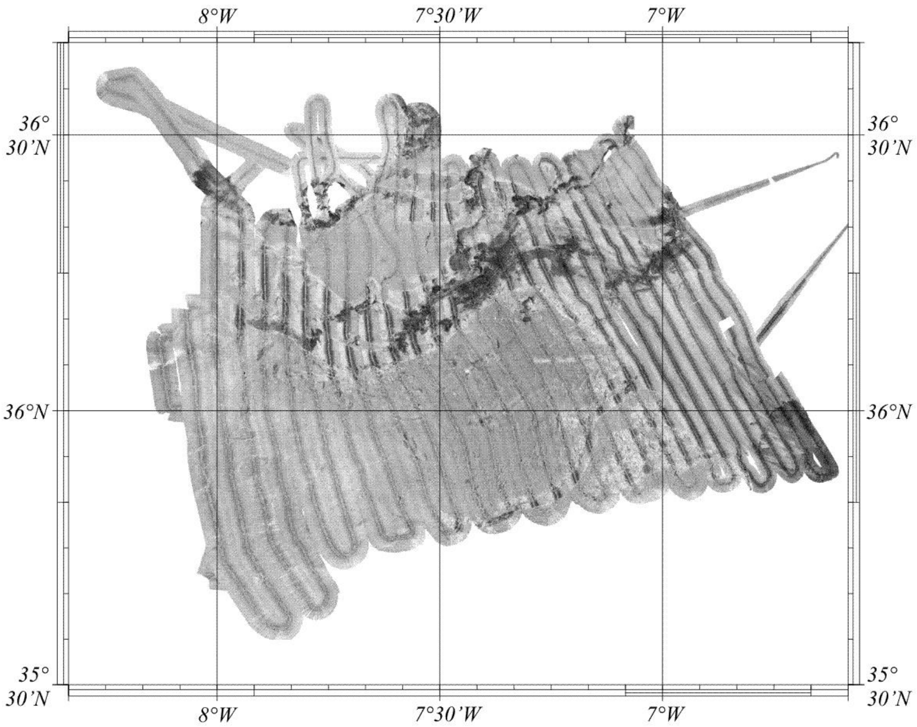

Figure 2: high resolution EM300 acoustic imagery map of the study area (see location on *figure 2, PART 1*).

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PART 3 - THE STUDY AREA

The area mapped during the CADISAR cruise is located between N35°35'/N36°40' and W6°35'/W8°20' (*figure 1*; *figure 1 and 2, PART 2*). The bathymetry ranges between 400 m in the NE corner of the map down to 1900 m in the southwestern side of the map. This zone is limited, in its eastern part, by the still undifferentiated MOW, and in its northern part, by the Guadalquivir Drift (*figure 1*).

The main core:

- in the south-east corner of the map (*figure 1*);
- drains the north (higher and intermediate) and south cores.

The higher north core (HNC, *figure 1*):

- in the north-eastern part of the study area;
- is drained by the Huelva Channel;
- crosses two submarine valleys respectively limited by the Cadiz and the Guadalquivir Ridges.

Note: The incision of these valleys can be due either to turbidity current or contour current activity.

The intermediate north core (INC, *figure 1*):

- in the northern part of the study area;
- Guadalquivir Ridge ⇨ INC separation from the north core;
- topographic high (N36°24'/W7°24') ⇨ INC divided into two branches; downstream, convergence of these branches ⇨ simple flow channeled by the Guadalquivir Channel.

The first inter-flow zone (IZ1, *figure 1*):

- located between INC and SC;
- flat and interpreted as a low-energy area.

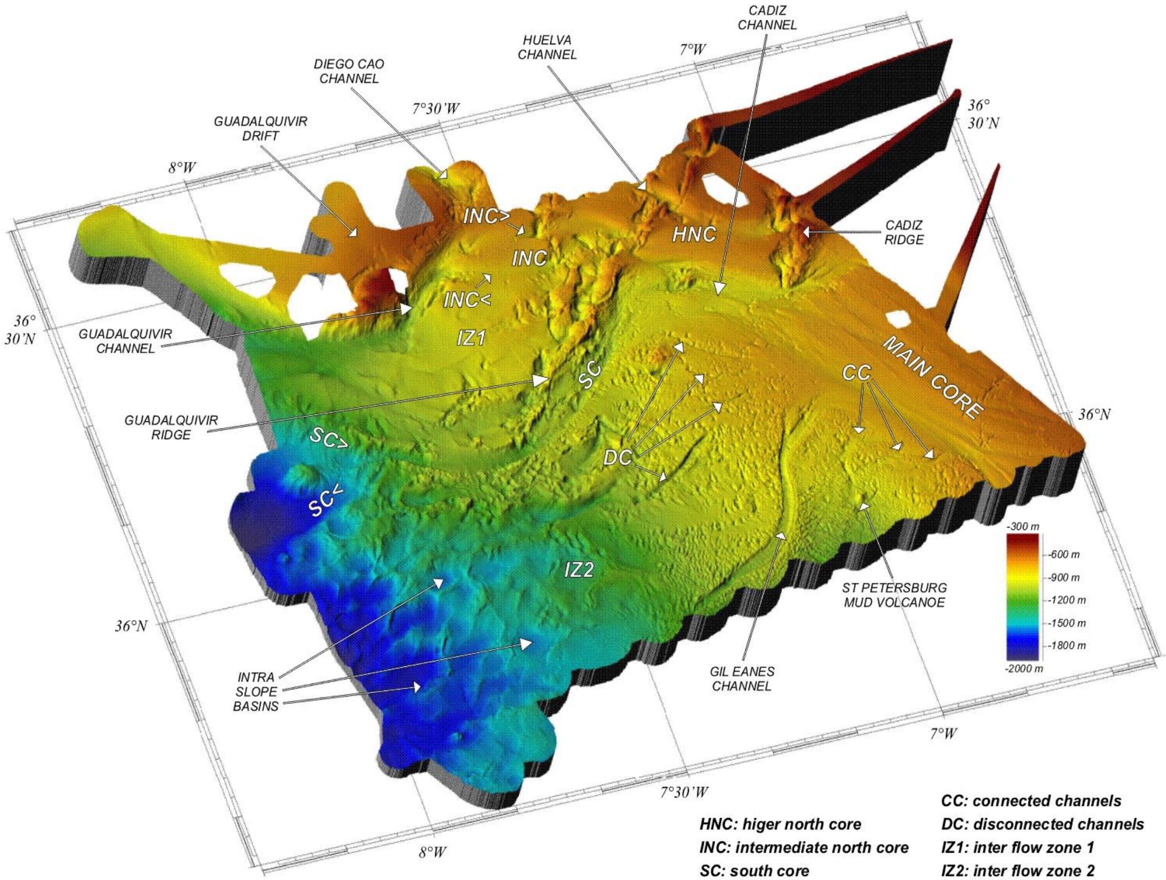

Figure 1: 3D bathymetry, toponymy, and main morpho-hydrodynamic outlines of the study area.

The south core (SC, *figure 1*):

- channeled by the Cadiz Channel;
- crosses the central part of the study area;
- SC first flows towards NW then, the Guadalquivir Ridge (*figure 1*) ⇨ change of direction towards SW; more distaly, due to the Coriolis force, SC flows again towards NW;
- to the western extremity of the study area, SC separates into two branches (SC> and SC<, *figure 1*); a topographic high (N36°9'/W8°) ⇨ SC> continues its progression towards NW, and SC< is deviated towards SW.

The second inter-flow zone (IZ2, *figure 1*):

- southward of SC and westward of the main core;
- eastern part characterized by many channels; one of them, the Gil Eanes Channel, is active and connected in its eastern part to the main core. Northward, four smaller and disconnected channels are visible (DC, *figure 1*). Southward, three smaller channels seem being connected to the main core (CC, *figure 1*);
- western part shows circular to egg-shaped depressions (*figure 1*); each one is bordered by 100-200 m high escarpment in the East and by a small topographic high in the West; these depressions are interpreted as large sediment failures, finally forming small intra slope basins.

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PART 4 - DISTRIBUTION OF THE MORPHO-SEDIMENTARY FACIES

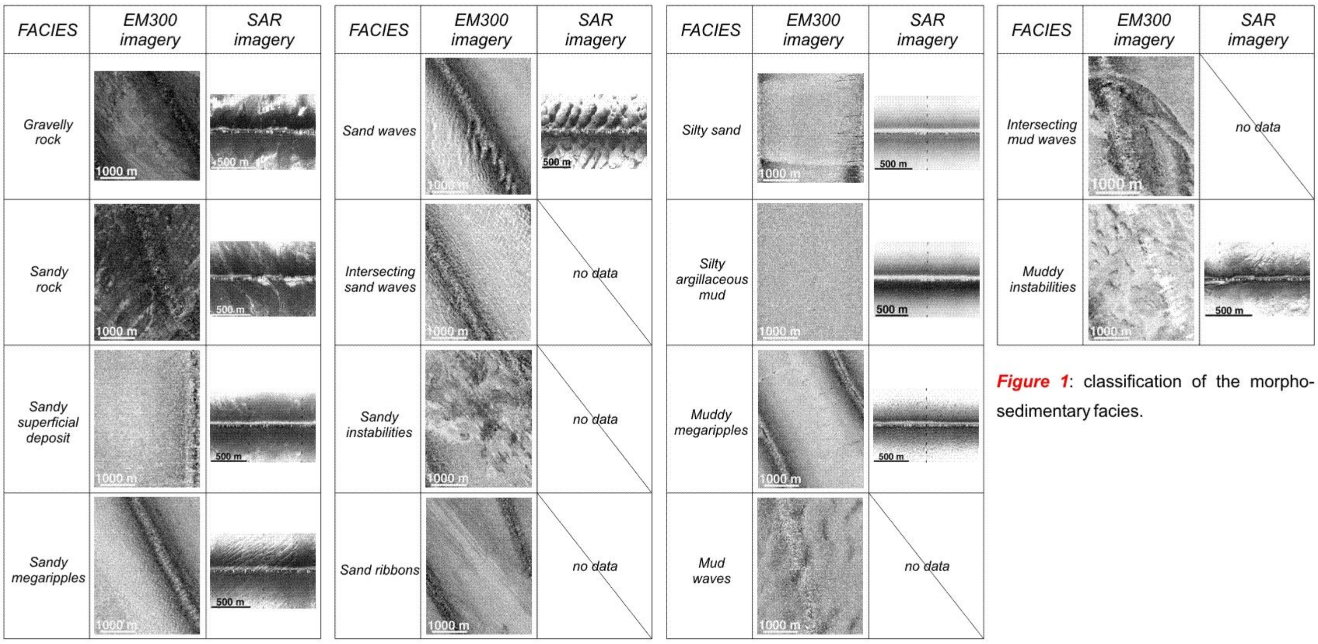

Figure 1: classification of the morpho-sedimentary facies.

It is possible to define fourteen morpho-sedimentary facies in the study area, using the ranges of reflectivity visible with the EM300 and SAR imagery (*figure 1*).

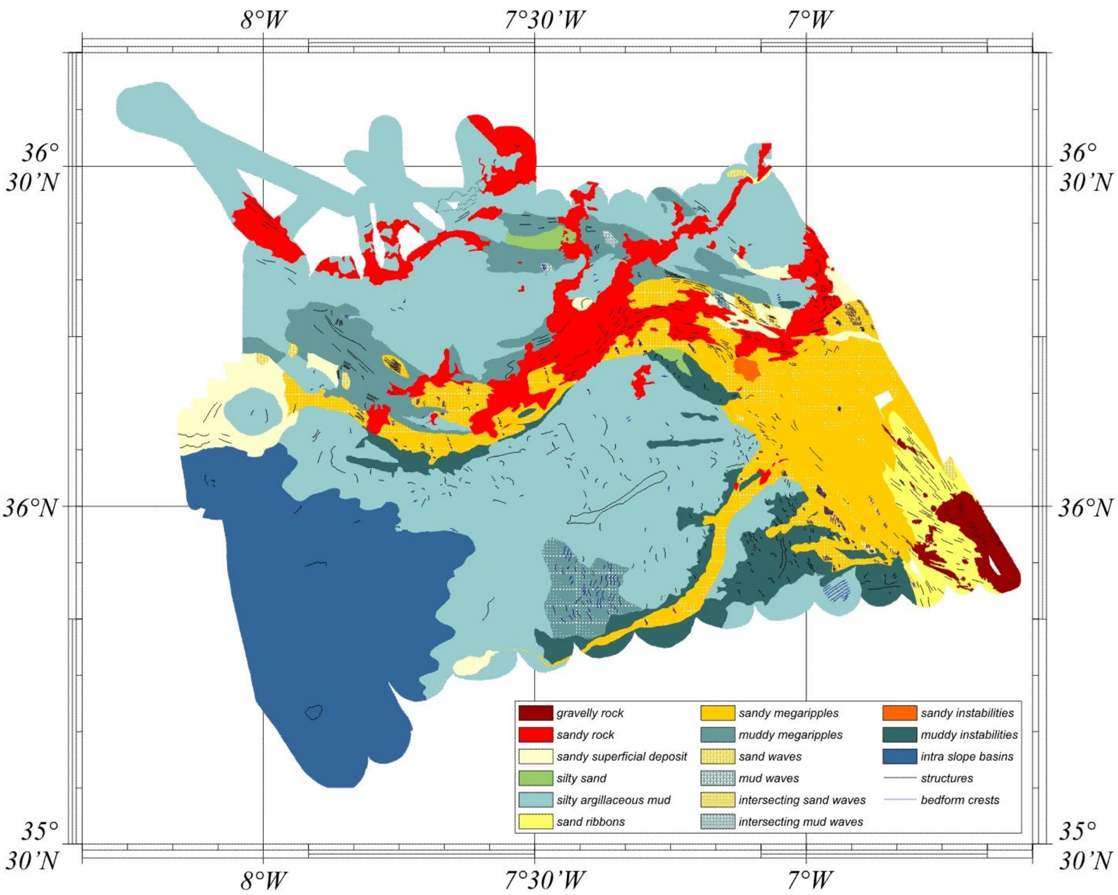

Figure 2: morpho-sedimentary facies distribution.

Recognition and interpretation of the morpho-sedimentary facies allowed to establish a map of the morpho-sedimentary facies distribution in the study area (*figure 2*). This map shows a logical repartition of the surface sediment. This organization allows to highlight erosion areas (abrasive action of the MOW) and deposit areas (lower flow velocities).

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PART 5 - THE GULF OF CADIZ: A GIANT CONTOURITIC LEVEE?

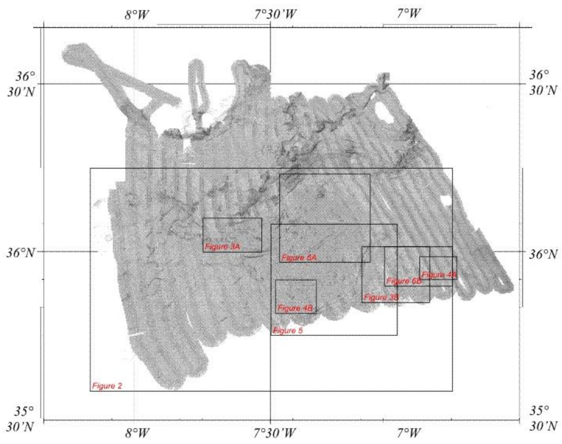

Figure 1: 3D imagery map of the study area.

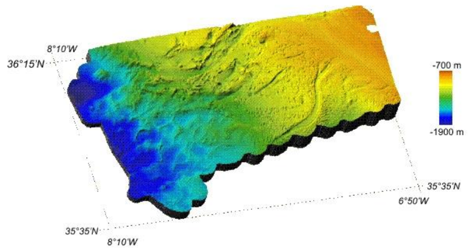

Figure 2: 3D bathymetry detail of IZ2 (see location on *figure 1*).

IZ2 (*figure 1 and 2*; see *figure 1, PART3*) shows evidence of sediment accumulation:

- high sedimentation rates: spilling of the main core and SC;
- failures scarps (*figure 3A and 3B; see figure 2, PART4*);
- sediment wave fields (*figure 4A and 4B; see figure 2, PART 4*).

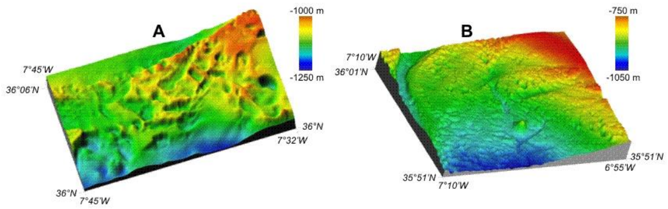

Figure 3: 3D bathymetry detail of failure scarps.

The crest orientation of sediment waves in the western part of the main core (*figure 4A; figure 2, PART 4*) and in the eastern part of IZ2 (*figure 4B; figure 2, PART 4*) suggests a westward direction of the MOW at these location.

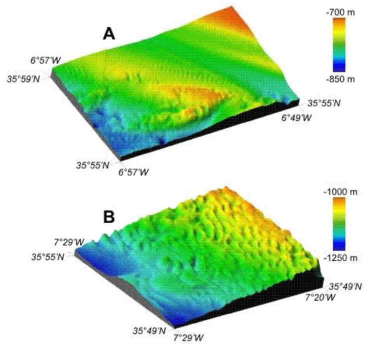

Figure 4: 3D bathymetry detail of sediment waves.

Erosive structures and coarse sediments (see *figure 2, PART 4*) covering the channel floor of the main core (see location on *figure 1, PART3*) indicate high MOW velocities. Conversely, sediment waves covering the topographic high bordering the main core (*figure 4B*) show deposition and a westward decrease of the main core velocity.

These observations suggest that IZ2 acts as a giant sedimentary levee built by stacked contourites deposited by loss of competency of the part of the MOW that flows over a sedimentary levee.

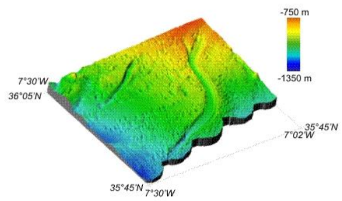

Figure 5: 3D bathymetry detail of the Gil Eanes Channel.

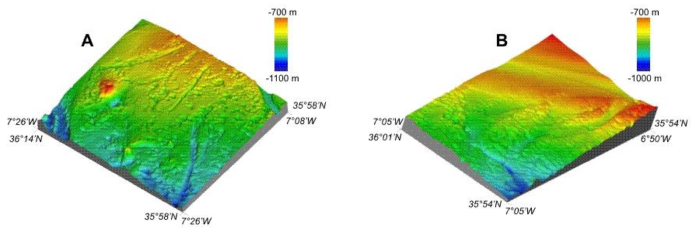

Figure 6: 3D bathymetry detail of the secondary channels.

The part of the main core that does not spill over IZ2 is drained by the Gil Eanes Channel (*figure 5;* high backscatter in *figure 1*). The topographic high and the intense deformation that appears on the north channel side (low backscatter in *figure 1*; see *figure 2, PART 4*) could be explained by the spilling of the channeled flow.

Important differences exist between channel located north and south of Gil Eanes.

Channels located north (DC, *figure 1, PART3*; *figure 6A*):

- low backscatter (*figure 1*);
- head several kilometers away from the main core.

Channels located south (CC, *figure 1, PART3*; *figure 6B*):

- high backscatter similar to the one observed in Gil Eanes channel floor (*figure 1*);
- head connected to the main core.

This would suggest that DC are ancient channel progressively filling and that CC are young forming channels.

These observations suggest that there is a north-south trend of channel formation with a sedimentary and/or tectonic origin. Tectonics already plays an important role:

- in the pathway evolution of the different MOW cores (split up of the main core into north and south cores);
- in the mud volcanoes formation (activity of an underlying accretion prism);
- in the important seismic activity observed in the Gulf of Cadiz (e.g. The Gorringe earthquake in 1969).