Supplementary Materials for

Messinian Atlantic-Mediterranean gateway restriction modified overflow and reshaped Atlantic deep waters

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Geological and Oceanographic settings

Since the Late Cretaceous, the geodynamic evolution of the Gulf of Cádiz and the western Portuguese margin has been governed by convergence between the African (Nubia) and Eurasian (Iberia) plates and the westward migration of the Alborán domain, culminating in the formation of the Gibraltar Arc[7]. Eastward subduction of Tethyan oceanic lithosphere beneath the arc drove the development of the *Gulf of Cádiz Accretionary Wedge* (GCAW, Fig. 1) during the Early–Middle Miocene, followed by gravitational collapse and emplacement of the *Allochthonous Unit of the Gulf of Cádiz* (AUGC, Fig. 1) between ~7.51 and 7.24 Ma, with deformation continuing into the Late Miocene[12, 24, 71-72]. Together, these tectonic processes generated a complex foreland basin system in the Gulf of Cádiz, extending from the Spanish margin/Coast up to the eastern Algarve margin, and bounded to the west by the Gil Eanes Fault[25]. Along the NW Algarve and Alentejo margins, the regional compressional tectonics caused uplift and the reactivation and inversion of major rift-related faults[25, 73]. Long-lived halokinesis further produced numerous Triassic salt structures and associated withdrawal sub-basins[25, 73].

In the foredeep domain, late Miocene sedimentation is bounded at its base by a regional erosional surface, the Basal Foredeep Unconformity (BFU), a regional erosional surface that marks the transition at ~8.2–8.0 Ma from a rifted passive margin to a flexural foredeep associated with the Betic–Rif orogeny[25, 58, 71]. Farther west, this tectonic reorganization corresponds diachronously to an older Lower Miocene unconformity (~20.5 Ma) on the NW Algarve[25, 59]. On the Alentejo margin, the principal regional unconformity is Middle Miocene in age (~14 Ma)[74, 75], and separates the highly deformed Mesozoic-Lower Miocene succession from overlying Upper Miocene-Quaternary strata. The overlying succession records syn- to

post-emplacement deposition dominated by hemipelagites, turbidites, contourites, reworked turbidites, and debrites[11,12, 21-23]. Sandy turbidites of the Guadalquivir Sands prograded southwestward from the Guadalquivir Basin into the Gulf of Cádiz during episodes of tectonic uplift in the late Tortonian and Messinian, reflecting strong tectonic control on sediment supply and basin reorganization[11, 40-42].

Present-day Mediterranean-Atlantic exchange (Fig. 1) is governed by a two-way circulation through the Strait of Gibraltar, involving eastward inflow of Atlantic surface waters and westward outflow of saline intermediate and deep waters[26]. This outflow forms the *Mediterranean Outflow Water* (MOW), a high-salinity (~36.5 g/kg) water mass that exits the Mediterranean across the Camarinal Sill (~284 m water depth), cascades downslope, and flows along the Gulf of Cádiz and the western Portuguese margin at depths of ~500–1400 m[27]. Downstream from the Camarinal Sill, the outflow progressively freshens, and increases in transport volume through entrainment of fresher East North Atlantic Central Water (ENACW) from above[26]. MOW subsequently spreads throughout the North Atlantic at intermediate depths, occupying a position below East North Atlantic Central Water (ENACW) and above the North Atlantic Deep Water (NADW), while interacting with Antarctic Intermediate Water (AAIW) and Subarctic Intermediate Water (SAIW) [28]. Beyond its regional expression, MOW contributes significantly to the NADW formation, both volumetrically and by supplying salt that preconditions convective sinking in the North Atlantic subpolar gyre[76]. As such, the MOW exerts a significant influence on the *Atlantic Meridional Overturning Circulation (AMOC)*[33, 34, 60]. Numerical simulations indicate that AMOC is sensitive to the MOW salinity[77], whereas the absence of MOW weakens the overturning circulation and leads to substantial climatic impacts, including reduced North Atlantic surface temperatures[4].

Atlantic-Mediterranean Connectivity throughout the Messinian Salinity Crisis

Accumulating evidence from recent multi-proxy studies on the evolution of the Mediterranean Basin highlights complex base-level fluctuations across the distinct stages of the Messinian Salinity Crisis. *Stage 1* is characterized by a continuous marine evaporitic record devoid of major stratigraphic interruptions or significant base-level drawdowns, implying a restricted yet persistent two-way exchange at the Atlantic-Mediterranean gateway[18, 78]. Consequently, the Mediterranean outflow between 5.97 and 5.60 Ma must have consisted of highly dense, hypersaline waters with progressively increasing salinities (probably ranging from ~110 to over 150 g kg^{-1} [15, 18, 44, 64]).

In contrast, *Stage 2* exhibits a bipartite evolution: an initial phase of restricted Atlantic-Mediterranean connectivity (5.60–5.56 Ma), followed by a second phase (5.56–5.54 Ma)

where gateway connectivity ceased entirely[43]. This isolation triggered a rapid, high-amplitude base-level drawdown driven by the Mediterranean's negative net hydrological budget. Finally, the subsequent Lago Mare stage remains the most enigmatic MSC interval due to its complex sedimentary record and mixed biota. Recent work on this stage suggests precession-driven, intermediate-to-high base-level variations[79, 80], with Andreetto et al.[79] advocating a regime of periodic activation and cessation of Atlantic-Mediterranean connectivity. These regional long-term observations strongly align with our proposed chronological framework and the documented variations in Mediterranean overflow intensity and density into the Atlantic Ocean during the uppermost Miocene

Figures

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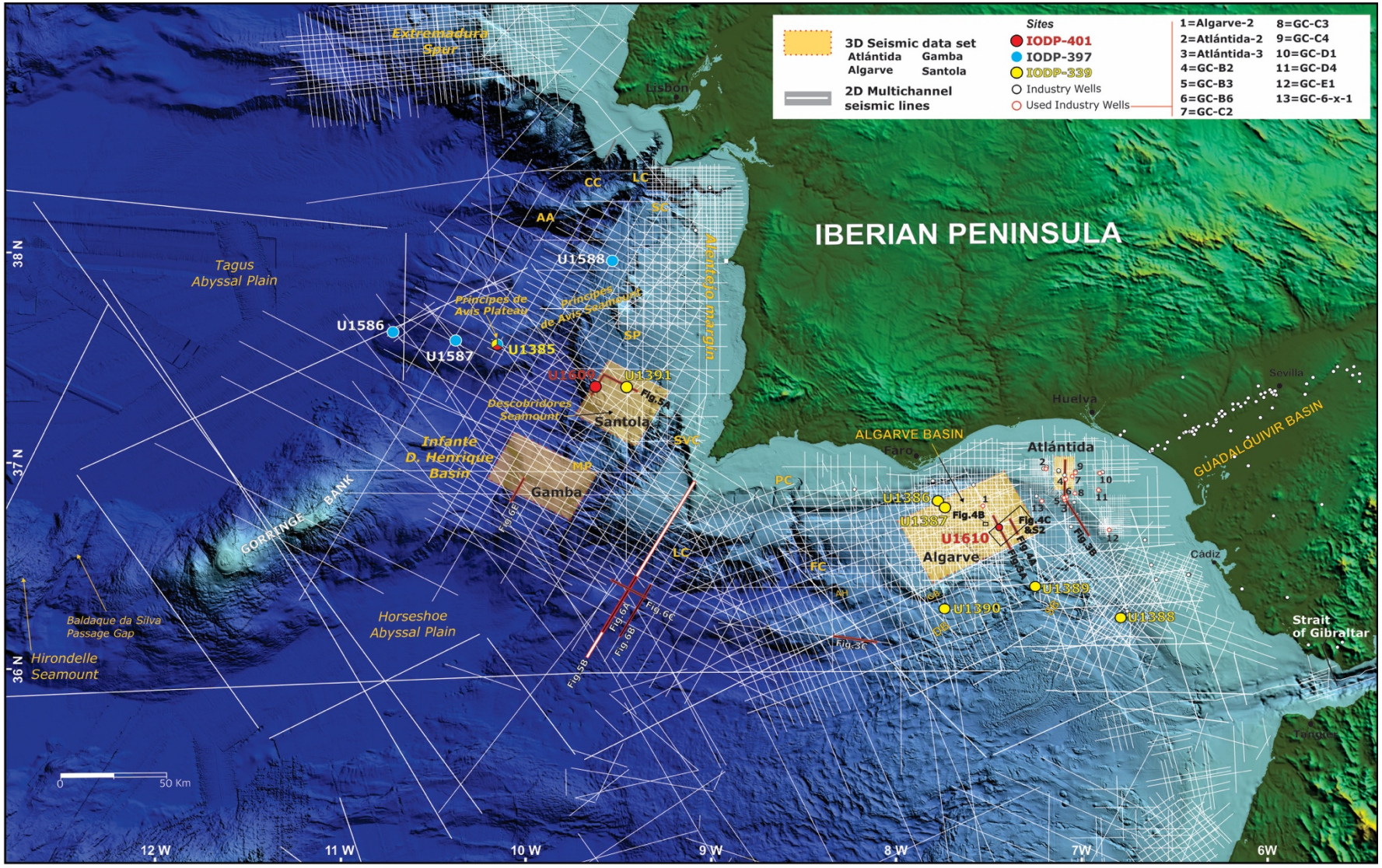
Figure S1. Base map with seismic and well datasets across the Gulf of Cádiz and the western Portuguese margin. Sites from the Integrated Ocean Drilling Program and International Ocean Discovery Program (IODP) Expeditions 339, 397, and 401 are also shown.



3D Seismic data set
Atlántida
Gamba
Algarve
Santola
2D Multichannel seismic lines
Sites
IODP-401
IODP-397
IODP-339
Industry Wells
Used Industry Wells
1=Algarve-2
2=Atlántida-2
3=Atlántida-3
4=GC-B2
5=GC-B3
6=GC-B6
7=GC-C2
8=GC-C3
9=GC-C4
10=GC-D1
11=GC-D4
12=GC-E1
13=GC-6-x-1
IBERIAN PENINSULA
Extremadura Spur
Lisbon
Tagus Abyssal Plain
Principes de Avis Plateau
Principes de Avis Seamount
Alentejo margin
Descobridores Seamount
Santola
Infante D. Henrique Basin
Gamba
GORRINGE BANK
Horseshoe Abyssal Plain
Baldaque da Silva Passage Gap
Hirondelle Seamount
ALGARVE BASIN
Faro
Huelva
Sevilla
Atlántida
GUADALQUIVIR BASIN
Algarve
Cádiz
Strait of Gibraltar
Tangier
U1586
U1587
U1588
U1385
U1390
U1391
U1386
U1387
U1610
U1389
U1388
Fig.5A
Fig.4B
Fig.4C &S2
Fig.4A
Fig.3A
Fig.3B
Fig.3C
Fig.6A
Fig.6B
Fig.6C
Fig.5B
Fig.6E
CC
LC
AA
SP
SVC
MP
PC
FC
AH
DC
38 N
37 N
36 N
12 W
11 W
10 W
9 W
8 W
7W
6W
0
50 Km

Figure S1

See attached PDF file

Figure S2. 3D visualization of a portion of Southern Channel using eXchroma SRGB color attributes extracted along key discontinuities (D_1 to D_7) in the area surrounding the IODP Expedition 401 Site U1610. That site penetrates until SU2 but not as deeply as D1 and D2. The seismic units below the discontinuities are shown. Location on panels within the channels and ridges sector, see Figs. 2 and *S1*.