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Late Miocene contourite channel system reveals intermittent overflow behavior

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ABSTRACT

Paleoceanographic information from submarine overflows in the vicinity of oceanic gateways is of major importance for resolving the role of ocean circulation in modulating Earth's climate. Earth system models are currently the favored way to study the impact of gateways on global-scale processes, but studies on overflow-related deposits are more suitable to understand the detailed changes. Such deposits, however, had not yet been documented in outcrop. Here, we present a unique late Miocene contourite channel system from the Rifian Corridor (Morocco) related to the initiation of Mediterranean Outflow Water (MOW). Two channel branches were identified consisting of three vertically stacked channelized sandstone units encased in muddy deposits. Both branches have different channel-fill characteristics. Our findings provide strong evidence for intermittent behavior of overflow controlled by tectonic processes and regional climatic change. These fluctuations in paleo-MOW intermittently influenced global ocean circulation.

INTRODUCTION

Plate-tectonic reconfiguration plays a major role in modifying global ocean circulation and poleward temperature gradients by opening and closing oceanic gateways (Knutz, 2008). Changes in the transport of saline Mediterranean Outflow Water (MOW) to northern latitudes are no exception, as the present-day MOW contributes to the Atlantic Meridional Overturning Circulation by as much as 15%, increasing the North Atlantic surface temperature by 1 °C (Rogerson et al., 2012). The occurrence of a late Miocene paleo-MOW therefore likely had an impact on global ocean circulation and associated climate change. Recently, Capella et al. (2019) suggested that initiation of this paleo-MOW contributed to both the $\delta^{13}\text{C}$ shift and global cooling.

General circulation models are regularly used to reconstruct the nature of changing connectivity between oceans and seas. However,

these models are not suited to simulate hydraulic controls of narrow gateways, generating results that differ from observations (Alammoud et al., 2010; Ivanovic et al., 2013). To reconstruct the detailed timing and nature of changing connectivity, a geological record is required. Critical information for reconstructing gateway overflows is most likely preserved in the sediments that accumulated at its exit, i.e., contourites (e.g., Toucanne et al., 2007).

Contourite features have been recognized in modern and ancient sedimentary records along continental margins and in deep-water settings. Despite growing scientific interest, these deep-marine systems remain relatively poorly understood (Rebesco et al., 2014; Stow and Smillie, 2020), since very few ancient contourite deposits have been identified in outcrops and cores (Hüneke and Stow, 2008; Mutti et al., 2014). Here, we describe an unprecedented archive for unravelling the initial stages of MOW and the controls on overflow behavior based on two ancient contourite channels in the former

Rifian Corridor, Morocco. These channels are associated with the late Miocene paleo-MOW, which played an important role in water-mass exchange with the Atlantic Ocean (Seidenkrantz et al., 2000).

REGIONAL SETTING

The South Rifian Corridor is part of the Rif-Betic Cordillera, an arc-shaped orogenic belt surrounding the Alborán Sea in the westernmost part of the Mediterranean (Fig. 1). This marine gateway evolved in the Tortonian as a southwestward-migrating foreland basin during the latest stage of Africa-Iberia collision (Sani et al., 2007). The main basins that recorded sedimentation are the Saiss-Gharb on the Atlantic side and the Taza-Guercif on the Mediterranean side of the paleo-Taza Sill (Fig. 1; Capella et al., 2017a). The studied sections are situated just north of the Saiss Basin, where the seafloor morphology contained subaqueous highs formed by the Prerif Ridges ("PR" in Fig. 1; Roldán et al., 2014) and the imbricate wedge (Prerifian Nappe in Capella et al., 2017a). The frontal part of this wedge forms the northern slope of the corridor, which consists of intraslope subbasins related to the main thrust faults.

SEDIMENTARY RECORD

We identified eight facies (F1–F8) associated with hemipelagic, gravitational, and contourite deposits (Table S1 in the Supplemental Material¹). The Sidi Chahed section corresponds to "Ben Allou" studied by Capella et al. (2017a), while the Kirmta section is newly recognized. Both sections are composed of three vertically stacked sandstone units consisting of a

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¹Supplemental Material. Table S1 (facies and facies association scheme with example pictures from the outcrops). Please visit <https://doi.org/10.1130/G47944.1> to access the supplemental material, and contact editing@geosociety.org with any questions.

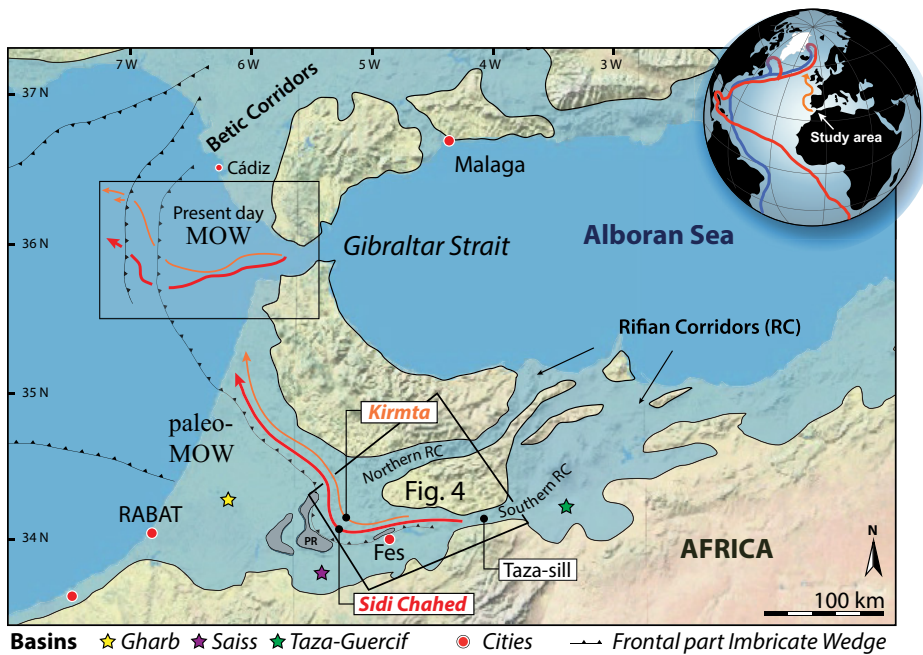


Figure 1. Paleogeographic reconstruction of the late Miocene western Mediterranean (modified after Capella et al., 2017a). Gray—subaqueous Prerif Ridges (PR). Red (lower) and orange (upper) arrows depict Mediterranean Outflow Water (MOW) branches. Globe shows MOW (orange) and main surficial (red) and deep-water circulation patterns (blue). Map data are ©2018 Google™ with topographic overlay from U.S. Geological Survey topographic maps (<http://earthpoint.us/TopoMap.aspx>).

compositional mix (sensu Chiarella et al., 2017) of bioclastic (dominantly shell, echinoid, and bryozoan fragments and foraminifera) and very fine- to coarse-grained siliciclastic sand. These sandstone units are encased in muddy sediments (F1 and F2), resulting in a sand/marl ratio of 0.73 for Sidi Chahed and 0.42 for Kirmta.

In the Sidi Chahed section, the sandstone units form the infill of large (roughly 500 m wide), up to 40-m-deep incisions (Fig. 2). Subordinate incisions (20–300 m wide) are filled (Fig. 2) by compound (up to meter-scale) three-dimensional (3-D) dunes (F5), two-dimensional dunes (F4), and slump deposits (F6).

Sandstone units in the Kirmta section are the infill of wider (>1 km) and shallower (5–15 m) incisions compared to Sidi Chahed (Fig. 3). These units consist of stacked 2-D dunes (up to 60 cm in thickness, F4). The two lowermost units are preceded by bigradational (silt- to fine sand-sized) planar bedsets (F3) with an average bed thickness of 10 cm and a lateral continuity exceeding 3 km (Fig. 3B). In both sections, the main sandstone intervals are bounded at the base and top by turbidites and occasionally by debris-flow deposits (F7 and F8, respectively; Figs. 2 and 3).

Paleocurrents, mainly measured from cross-bedding, indicate a dominant westward direction for the Sidi Chahed and a northwestward direction for the Kirmta sections (Figs. 2 and 3). Gravity-driven deposits, such as turbidite (F7) and slump deposits (F6), show paleocurrent

directions that are almost perpendicular to the main trends of the dunes (Figs. 2 and 3) and are subparallel to the southwest-directed paleoslope.

Paleodepth estimates from benthic foraminifera indicate a physiographic domain between 150 and 400 m water depth, equivalent to an outer shelf to upper/middle continental slope (Capella et al., 2017a). The tectonically confined corridor and proximal location to the gateway resulted in steep margins (Longhitano, 2013) prone to gravitational depositional processes.

DECODING THE PALEO-MOW

The investigation of the Kirmta outcrop allowed us, for the first time, to analyze the spatial distribution and time variations between both sections. This new information enhanced the paleogeographic reconstruction, sedimentological interpretation, and understanding of the hydrodynamic setting.

Sidi Chahed and Kirmta, located 10 km apart, are situated ~120 km west of the paleo-Taza Sill (Fig. 1), where they occupy a position against the main thrust fault zone. The paleo-Taza Sill was a submerged high controlling Atlantic-Mediterranean water exchange in the late Miocene (Capella et al., 2017a). The system is thought to have acted in a similar way as the present-day MOW at the Camarinal Sill in the Strait of Gibraltar (Baringer and Price, 1999; Legg et al., 2009), where Mediterranean water was able to flow over and cascade down the sill

into the Saiss Basin, generating a dense paleo-MOW that was deflected to the right (north-northeast) by the Coriolis force.

The main sandstone units are interpreted as contourite channel fills, part of an extensive contourite channel system. The interaction with partially incised, interstratified slump deposits (Fig. 2C), and the co-occurrence of shallow- and deep-marine bioclastic and foraminiferal assemblages that were subsequently reworked and accumulated within the along-slope channels by bottom currents all serve as evidence for an up-slope sediment source. Additional evidence of erosion and sediment supply lies in the presence of middle Miocene white marls (Figs. 2 and 3; Sani et al., 2007) and Triassic bipyramidal quartz of the Keuper facies (Herrero et al., 2020), which was incorporated in the imbricate wedge. These sediments were sourced by both down- and along-slope processes, whereas erosion was induced by bottom currents.

Foraminifer assemblages, similar for both sites, indicate that deposition of the Sidi Chahed and Kirmta sections occurred between 7.8 and 7.51 Ma (Capella et al., 2017a). Despite coeval activity, both sections show morphological differences in channel geometry and channel fill related to different hydrodynamic properties (deeply incised, narrow channels filled by 3-D and 2-D dunes and interstratified slump deposits in Sidi Chahed versus shallow, wide channels filled by 2-D dunes in Kirmta). Hydrodynamic differences are also observed from the differences in sand/marl ratios. Based on bed-form types (F3, F4, and F5) and their characteristics (Table S1; Stow et al., 2009), Sidi Chahed was influenced by higher-velocity bottom currents (up to 1 m s^{-1}) compared to Kirmta ($<0.5 \text{ m s}^{-1}$).

By comparison with the present-day MOW through the Gibraltar gateway, the proximal sector of the Gulf of Cádiz contourite system (GoCCS; Fig. 1) also has two main channels occupying the middle slope at different depths due to the circulation of the lower and upper branches of the MOW (Hernández-Molina et al., 2014). The similarities in geographic and depositional setting, channel distribution, and large morphological elements between the GoCCS and the Rifian Corridor indicate that hydrodynamic and feedback processes associated with the MOW acted in a similar way. It is envisaged that bifurcation of the paleo-MOW, similar to the flow bifurcation recognized in the Gulf of Cádiz (Hernández-Molina et al., 2014), took place in the Saiss Basin, separating the paleo-MOW into two branches that occupied different depths along the slope of the corridor. The lower branch (Sidi Chahed) occupied the deeper southern subbasin, and the upper branch (Kirmta) occupied the shallower northern subbasin (Fig. 4).

Studies in the GoCCS (Baringer and Price, 1999; Legg et al., 2009) have also shown that

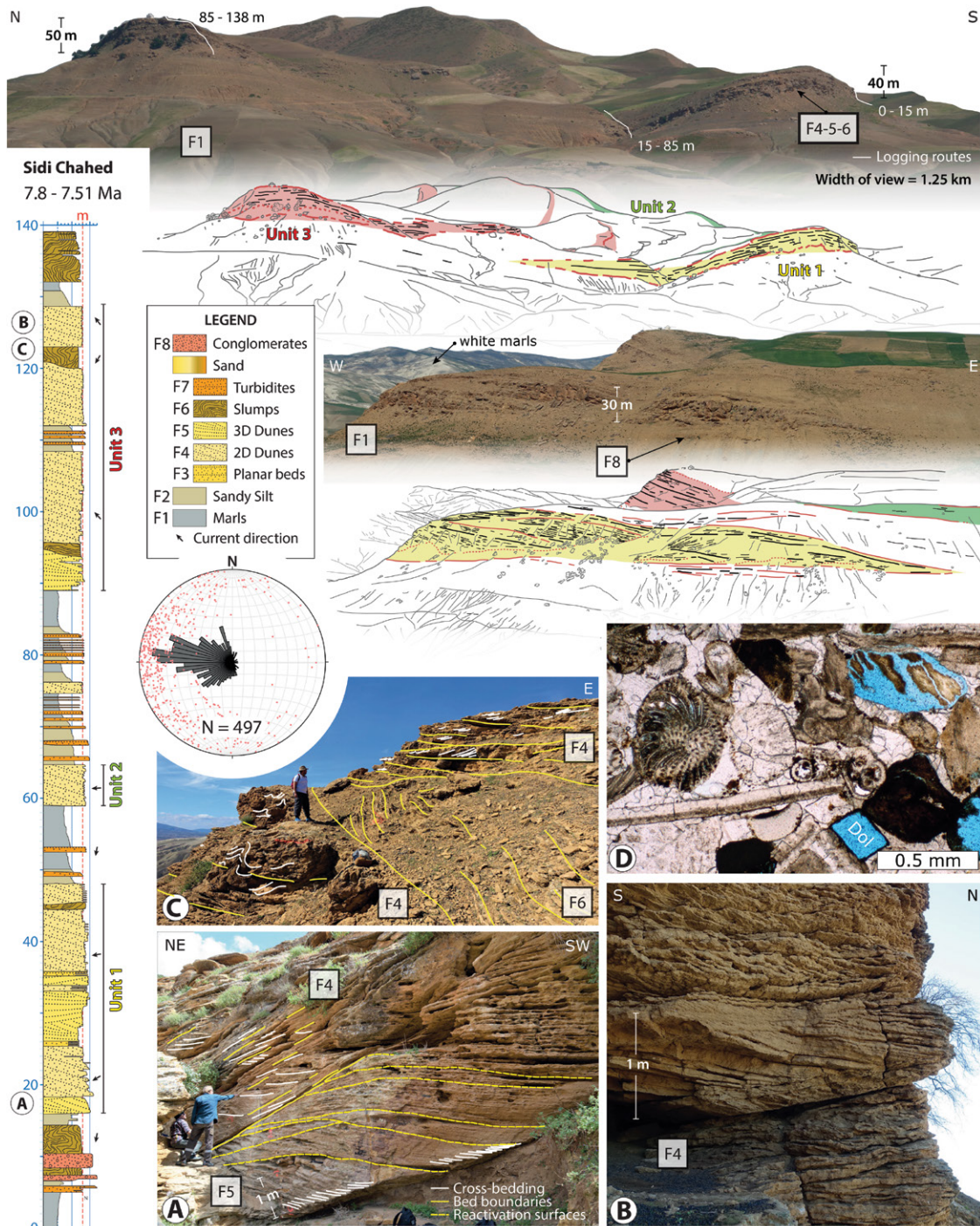


Figure 2. Sedimentary log, panoramic pictures, and interpretations for the Sidi Chahed section (Morocco; 34.101566°N, 5.301466°W). Three sand units (from old to young; yellow, green, and red) represent channel-fill sequences. Rosette diagram shows paleocurrent directions. (A) Basal fill sequence of sandstone unit 1. (B) Typical stacking pattern of facies F4. (C) Two bedsets of facies F4 separated by F6. Beds below F6 show soft-sediment deformation, and overlying beds are erosive. Note near-perpendicular difference in paleocurrent directions. (D) Thin section with mixed compositional sand of facies F4, and transported, exsolved dolomite (Dol) rhomb.

the MOW consists of the vertical distribution of three Mediterranean water masses (Modified Atlantic Water, Levantine Intermediate Water, and Mediterranean Deep Water; e.g., GRIDA, 2013). The bifurcation of the MOW into two branches, upper (MU) and lower (ML) MOW (Hernández-Molina et al., 2014), is the result of partial mixing of intermediate and deep Mediterranean waters. Consequently, we can infer a similar vertical distribution of water masses in the Mediterranean during the late Miocene, which agrees with numerical models proposed by de la Vara et al. (2015).

CONTROLS ON OVERFLOW

The occurrence of two channel branches consisting of three vertically stacked sandstone units encased in muddy deposits, with different channel-fill characteristics for each branch, provides strong evidence for an intermittent behavior of the paleo-MOW during the late Tortonian. This intermittency is also evident from (1) subordinate erosional features that indicate migration and/or reactivation of the bottom current cores, (2) alternating changes in dune morphology and sediment characteristics, and (3) tidal signatures (Capella et al., 2017a). This indicates that inter-

mittency of the paleo-MOW was controlled by different hydrodynamic processes acting at different physical and time scales.

Tectonic Processes

Two important tectonic events are recorded in the late Miocene (Capella et al., 2017b): (1) a regional compressional event around 8.4–7.8 Ma, culminating in the emplacement of the imbricate wedge just before the onset of contourite deposition, and (2) the transition from thin- to thick-skinned contraction, which happened around the Tortonian-Messinian boundary.

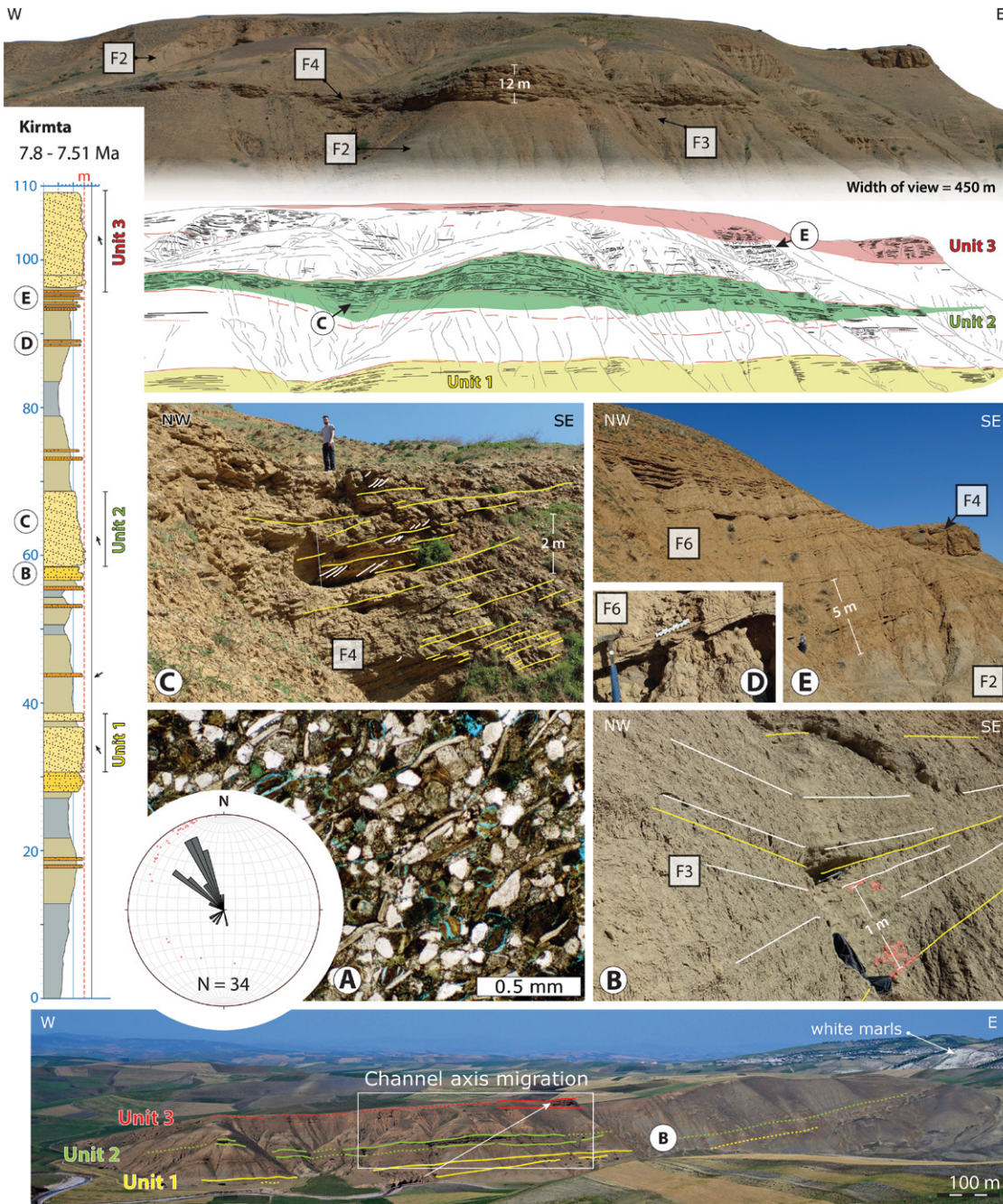


Figure 3. Sedimentary log (see Fig. 2 for legend), panoramic pictures, and interpretations for the Kirmta section (Morocco; 34.170855°N, 5.239288°W). Rosette diagram shows paleocurrent directions. (A–B) Facies F3. (C) Sandstone unit 2 with tabular cross-stratified beds (F4). (D–E) Facies F6, with turbidite deposits below uppermost sandstone unit.

Interestingly, between these two major tectonic events, a period of relative tectonic quiescence occurred from ca. 7.8 to 7.25 Ma, coinciding with the development of the recognized contourite channel system. Nevertheless, the northeastward, upslope migration of the three stacked contourite channels, observed from the channel axis distribution in the outcrops (Figs. 2 and 3), suggests that the imbricate wedge was tectonically active and migrated southwestward, intermittently affecting the evolution of the depositional system. These tectonic processes likely increased downslope sediment supply by creating slope instability. Additionally, they might have been responsible for channel migration resulting from slope and sill reconfigura-

tions. Particularly, the reconfiguration of the sill would have significantly impacted the dynamics of Mediterranean-Atlantic water exchange and thus the behavior of the paleo-MOW.

Climatic Processes

A relationship between long- and short-term climatic processes and the activity of the paleo-MOW is recognized at different scales, but the lack of high-resolution age constraints hampers our ability to provide detailed evidence of the dynamics between the upper and lower paleochannels. Observations from the GoCCS show that a stronger MOW in the deeper channel is linked to glacial periods, which are associated with higher aridity in the Mediterranean and thus

an increase in the density of Mediterranean Deep Water and intensification of the MOW (Llave et al., 2006). This implies that the MOW favors either the upper or lower channel based on its density characteristics because of tectonic- and climatic-induced effects on the Mediterranean water masses. The late Miocene was not severely influenced by eccentricity (glacial-interglacial) cycles but was dominated by precession (e.g., Sierró et al., 1999). Precessional cyclicality was therefore likely the driving force behind the intermittent behavior of the paleo-MOW. Smaller-order changes in the hydrodynamic characteristics of the overflow are likely related to millennial and seasonal changes in climatic conditions (e.g., Gladstone et al., 2007).

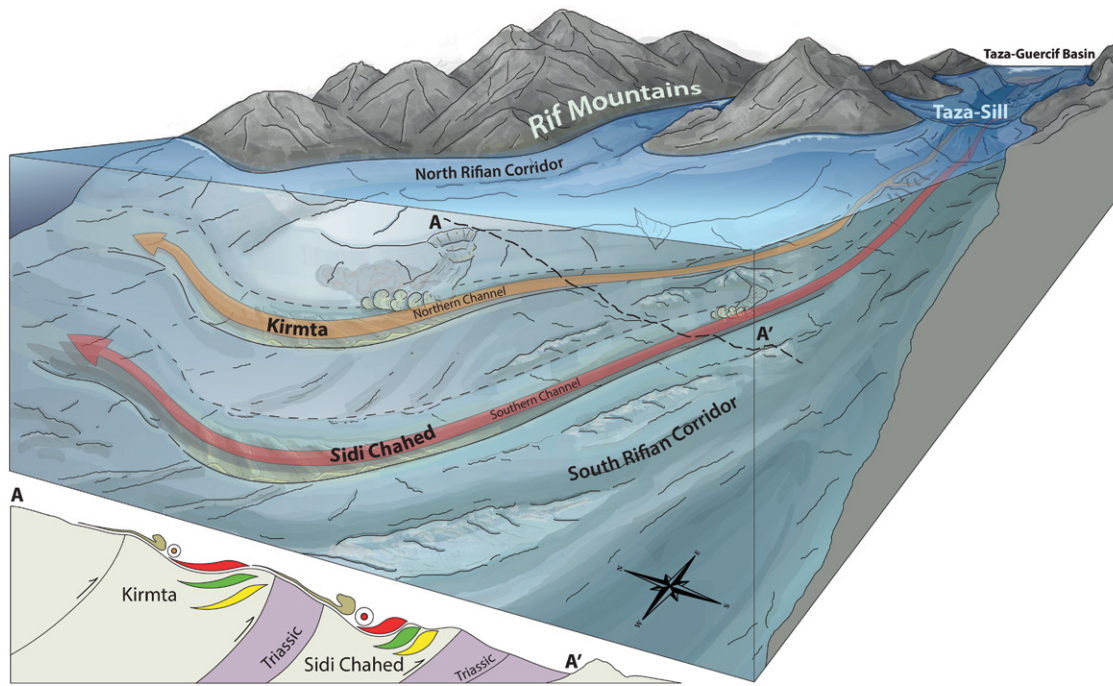


Figure 4. Paleogeographic model of the late Miocene Rifian Corridor (Morocco) with lower (red) and upper (orange) branches of paleo-Mediterranean Outflow Water (MOW). Cross section A-A' shows intraslope subsidence that act as fairways in the frontal part of the imbricate wedge and are filled by three vertically stacked, color-labeled (1–3) sand units. Circles depict location of core for each paleo-MOW branch.

IMPACT ON THERMOHALINE CIRCULATION

The late Miocene overflow was modulated by a complex hierarchy and interplay of processes. Studies across the Strait of Gibraltar have also demonstrated that overflow processes are affected by a variety of control factors at different scales (e.g., Schönfeld and Zahn, 2000; Llave et al., 2006). This indicates that understanding these late Miocene fossil contourite deposits can significantly help us to better understand changes in the behavior of overflows and their role in global ocean circulation.

In terms of consequences on Atlantic Ocean circulation, a deeper input of MOW will reduce the upper-ocean salinity in the Atlantic Ocean, while a shallower input will increase it. Saltier near-surface Atlantic water is usually associated with stronger deep convection and overturning (Rahmstorf, 2006; Kuhlbrodt et al., 2007). This impact, however, also depends on the ambient stratification and mixing of the Atlantic Ocean, which we cannot infer from these records. Furthermore, as these sedimentary records represent an early stage of paleo-MOW formation, it is unclear how much time it took to fully establish the MOW in the Atlantic. Despite these uncertainties, less input of salt and heat from the MOW would have weakened the Atlantic Meridional Overturning Circulation, while the depth of the input would have impacted the connection with surface-water properties, providing a less direct influence.

The intermittency of overflows resulting from tectonic events and climatic variations at precessional to seasonal time scales is currently not considered in models because proper sedimentary records are lacking. This record

shows that intermittency is possible on such time scales, and more evidence of such behavior should be obtained from similar systems, such as the Denmark Straits, Faroe Bank Channel, Red Sea, and Gulf of Cadiz.

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